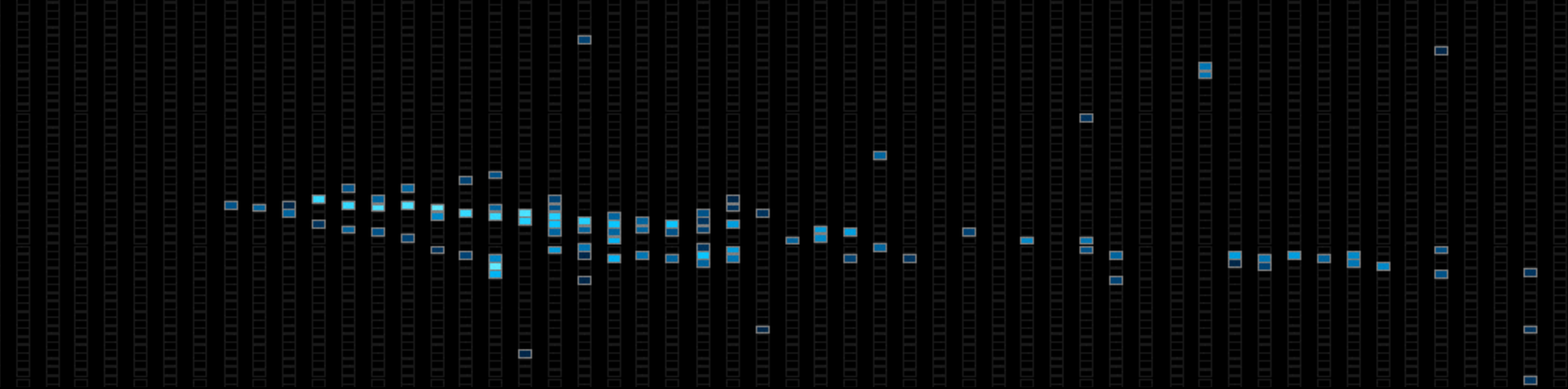
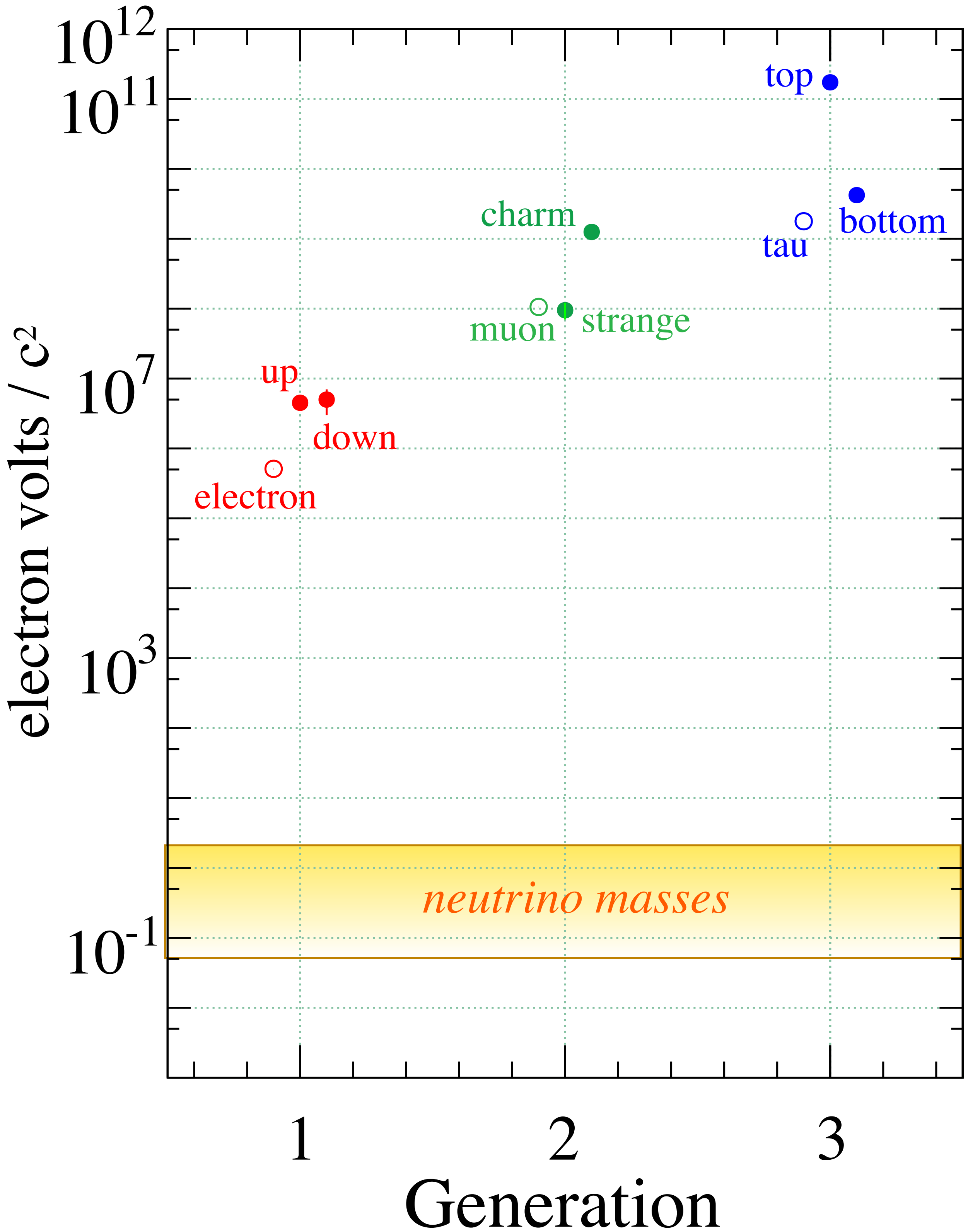


Exploring Neutrinos via Oscillations in the Atmosphere, at Reactors, and at Accelerators

Mark Messier
Indiana University

August 7, 2015



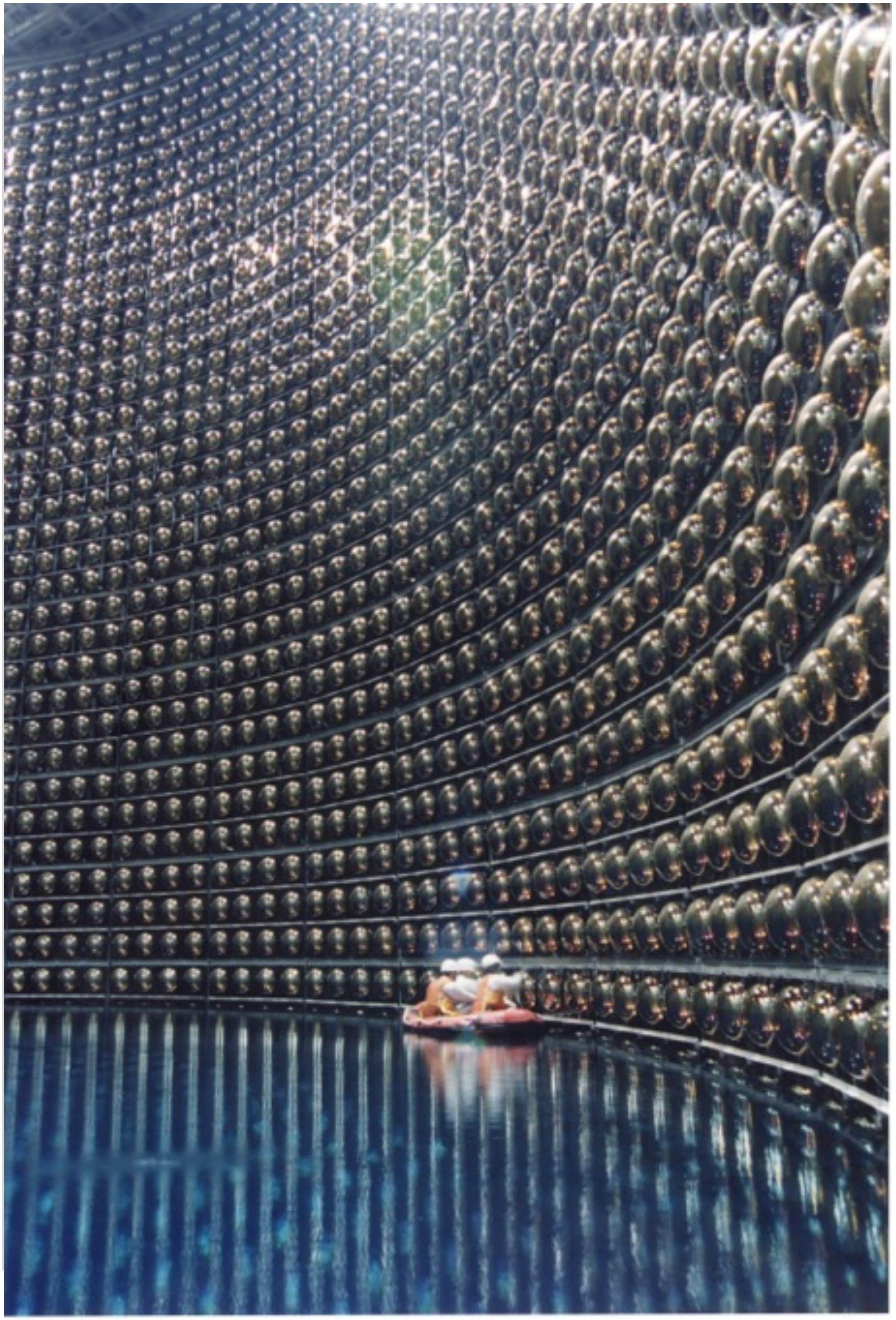
see-saw mechanism

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \nu_L & \nu_R \end{bmatrix} \begin{bmatrix} 0 & m \\ m & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$\lambda \simeq \frac{m^2}{M} \simeq \frac{(1\ \text{GeV})^2}{10^{11}\ \text{GeV}} = 0.01\ \text{eV}$$

Neutrino Mass

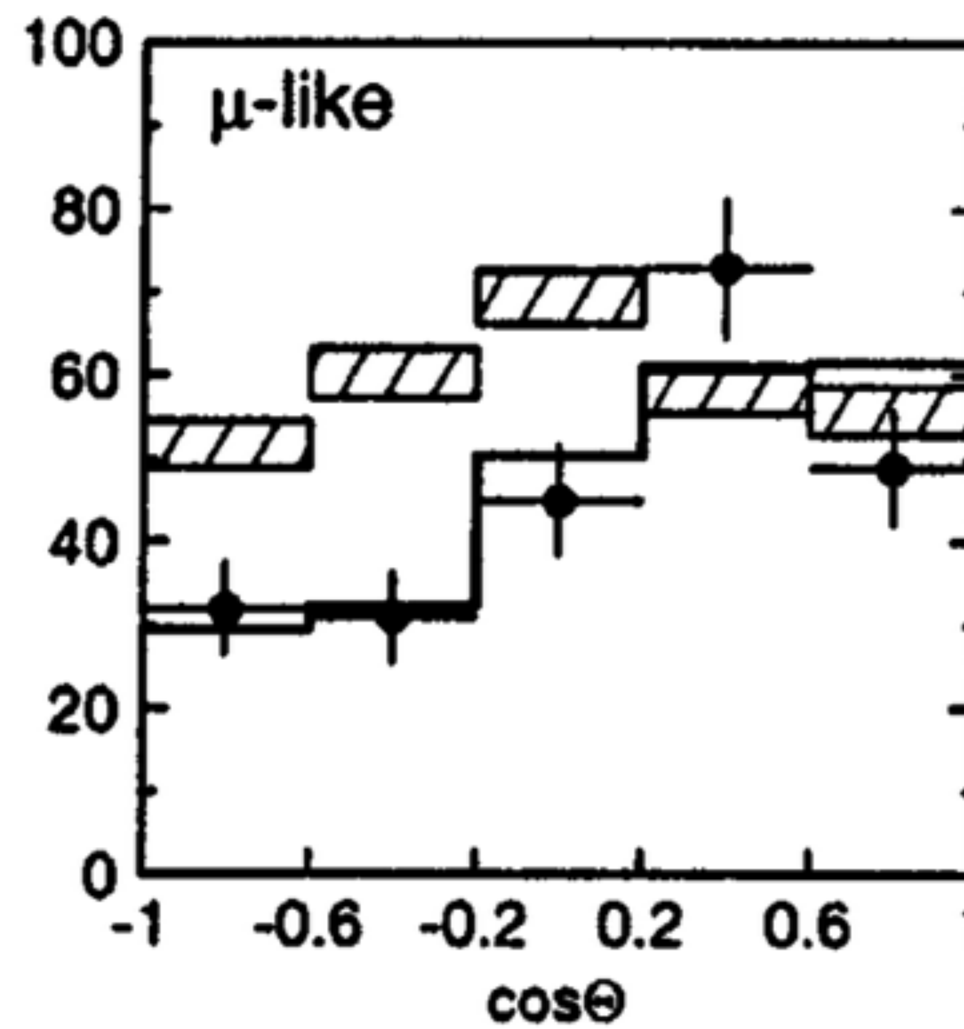
Neutrino masses and mixing are a window on physics approaching the GUT scale



Super-Kamiokande

<u>Mass found in elusive particle; Universe may never be the same</u>
New York Times, page 1, June 5, 1998

Evidence for oscillation of atmospheric neutrinos,
Phys.Rev.Lett.81:1562-1567,1998
4400+ citations to date, #24 all time



Neutrino oscillations

$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert$ $\simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$ $\nu_\mu \longrightarrow \nu_\tau$	$\nu_e \longrightarrow \nu_e$ $\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

Neutrino mass textures

$$U_{e3} = \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$$

$$\frac{\sqrt{\Delta m^2_{31}}}{2}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

normal mass ordering

$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad \sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$U_{e3} = \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

inverted mass ordering

$$\sqrt{\frac{\Delta m^2_{31}}{2}}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

follows hep-ph/0510213

Measurements

- θ_{12}
- θ_{13}
- θ_{23}
- δ_{CP}
- Mass ordering
- Dirac/Majorana

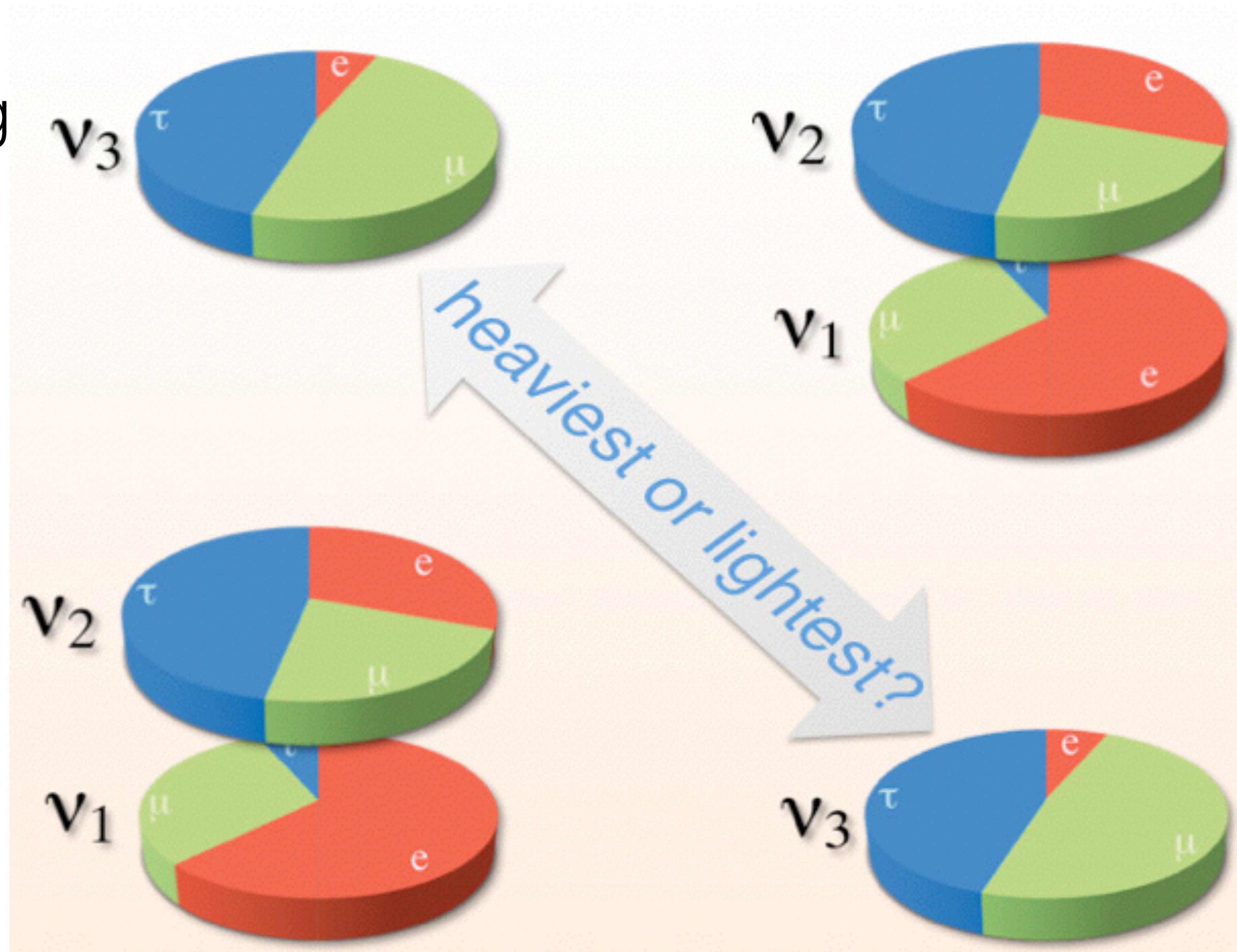
Extrapolate to GUT scale

$$|Y_{\mathrm{B}}| \simeq 2.4 \times 10^{-11} |\sin\delta| \left(\frac{\sin\theta_{13}}{0.15}\right)\left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)$$

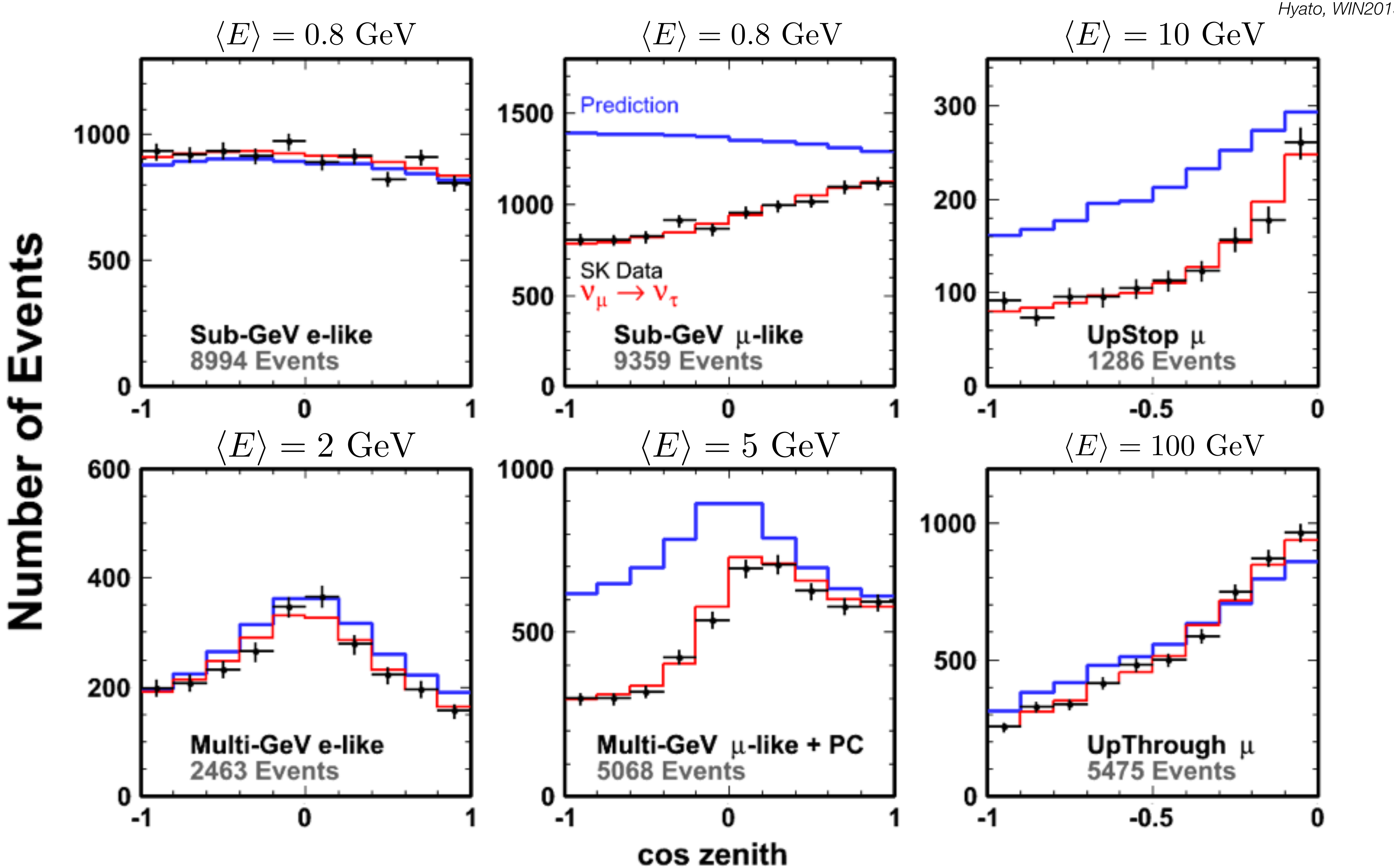
for example Pascoli, Petcov & Riotto PRD2007

Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?

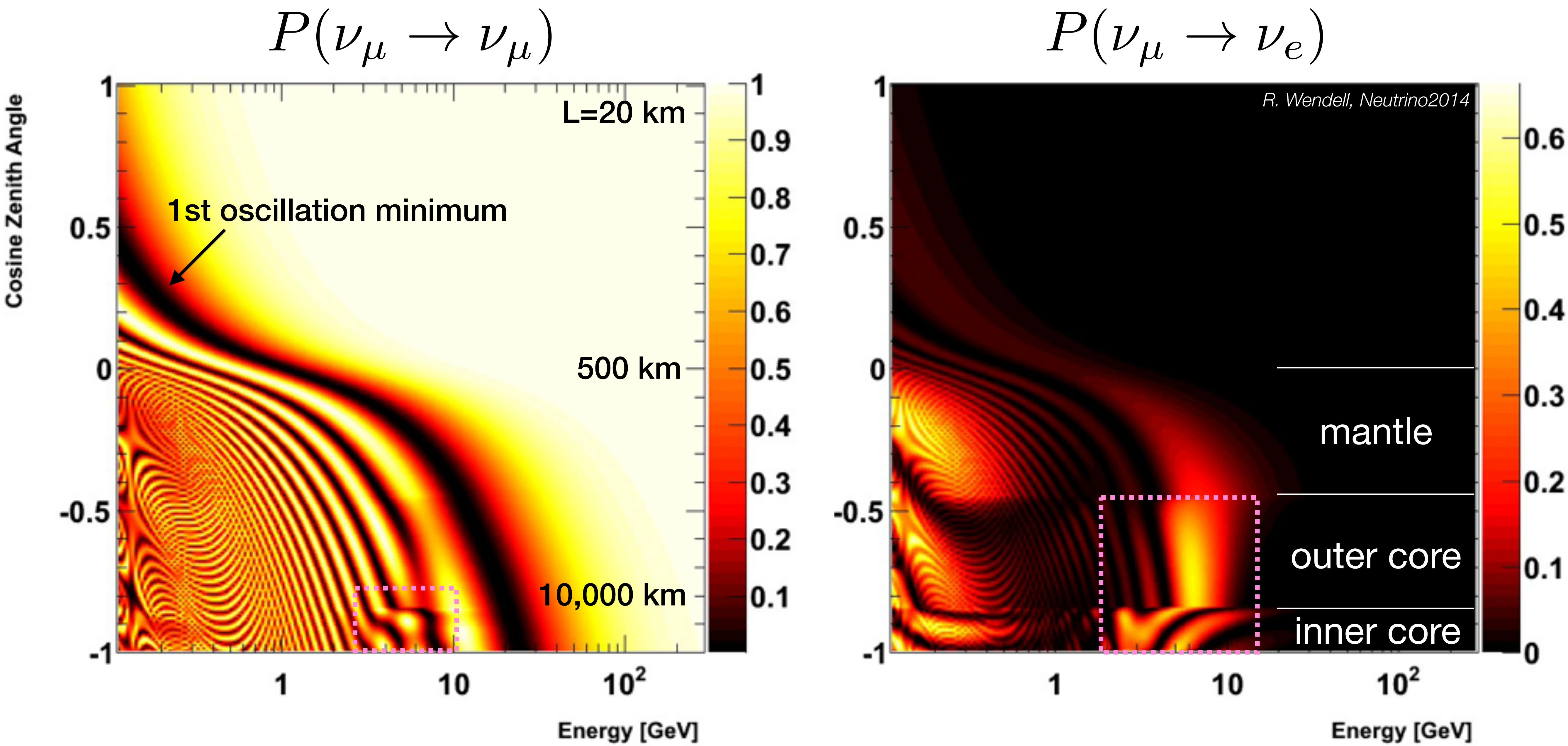


Hyato, WIN2015



Super-Kamiokande Atmospheric Neutrinos

Many sub-samples considered to access different energies, and flavors



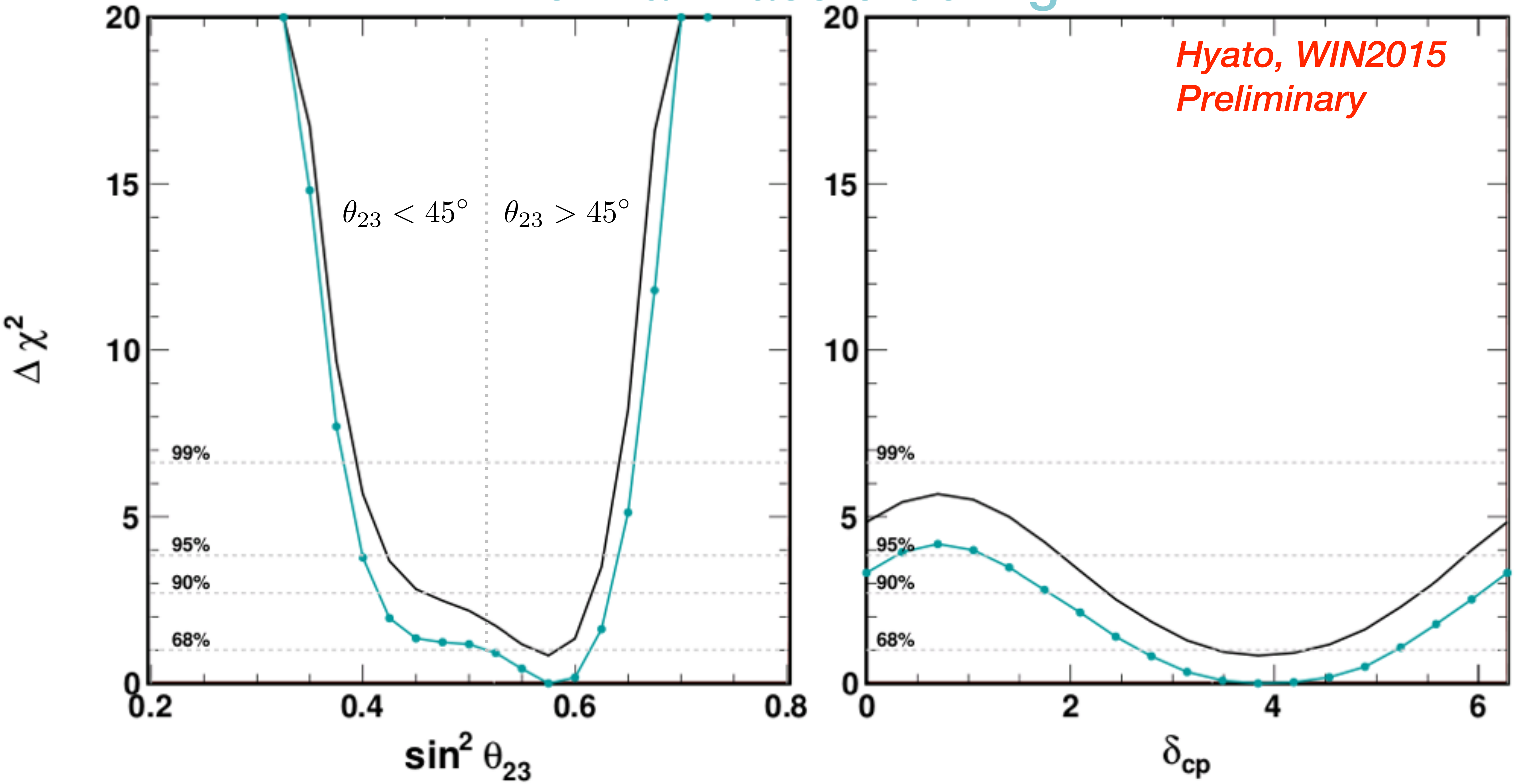
- Matter effects become important near 10 GeV in the most upward-going bins
- Need large exposure to overcome $E^{-1.7}$ power-law fall in spectrum and the effects of having mixed ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

Atmospheric neutrinos

Oscillation probabilities vs. zenith angle and energy

Inverted mass ordering

Normal mass ordering

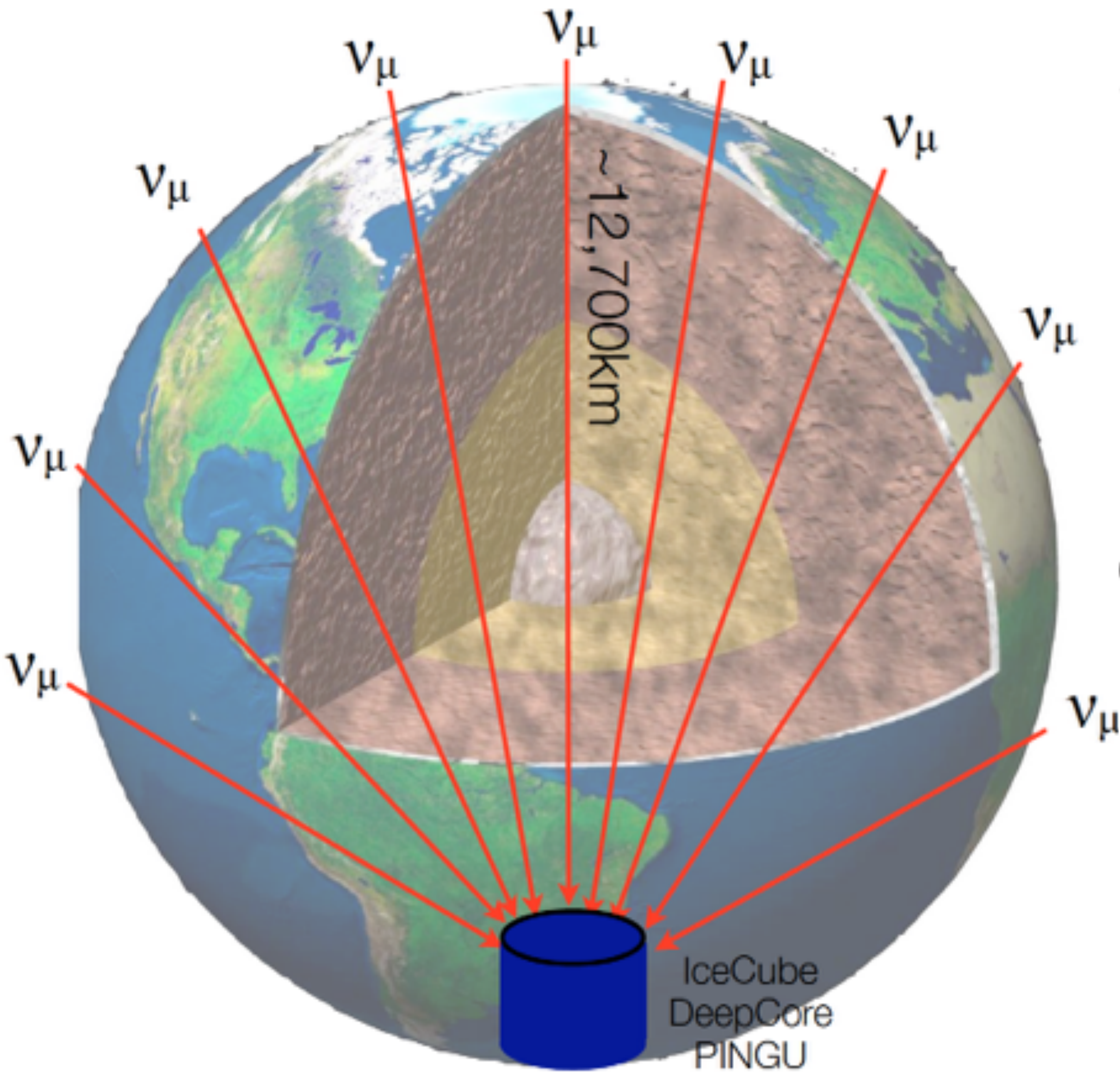


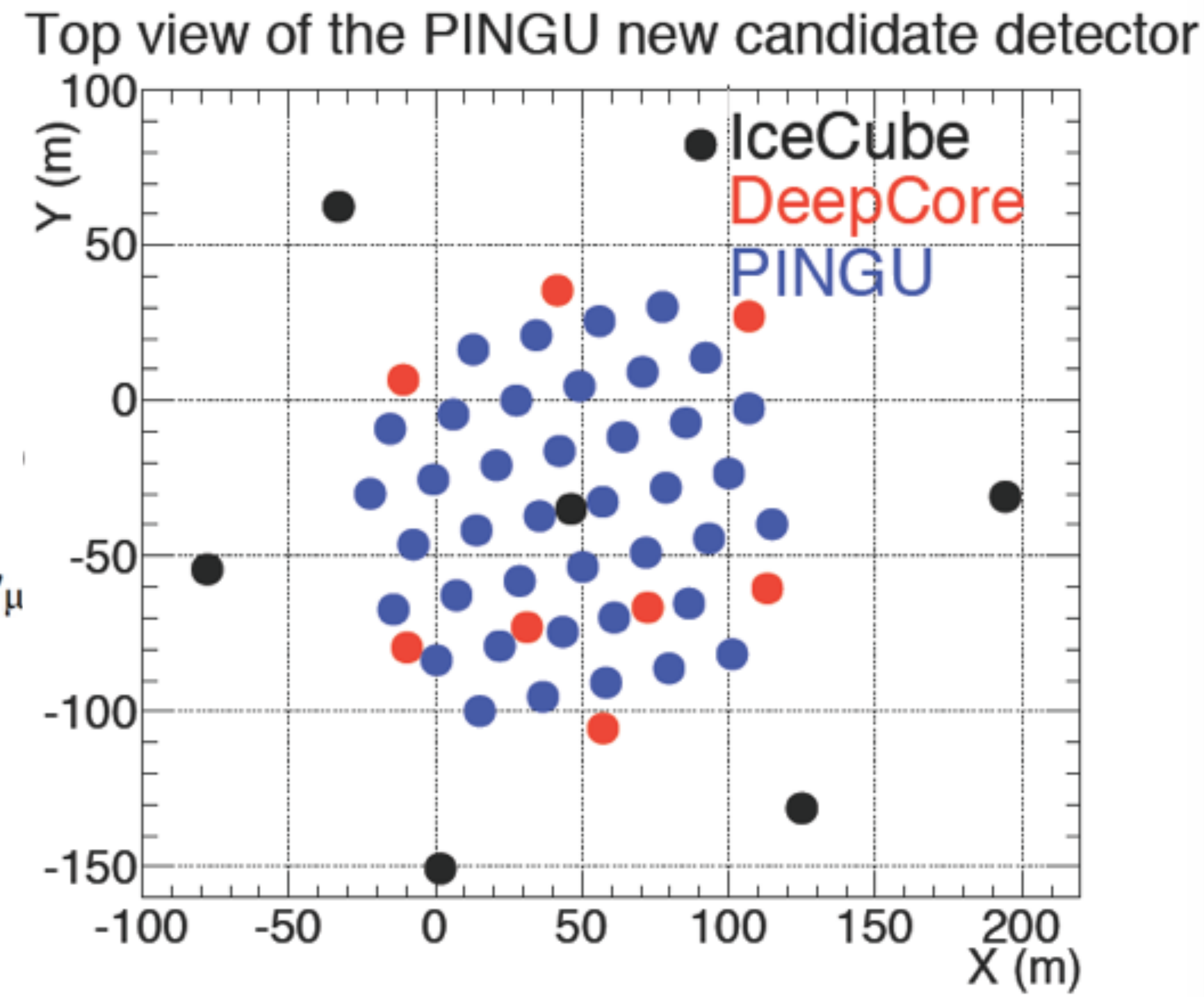
Super-Kamiokande Atmospheric Neutrinos

~1 sigma preference for

- normal mass ordering
- $\theta_{23}>45^o$
- $\pi<\delta_{CP}<2\pi$

D. Grant &
arXiv:1401.2046

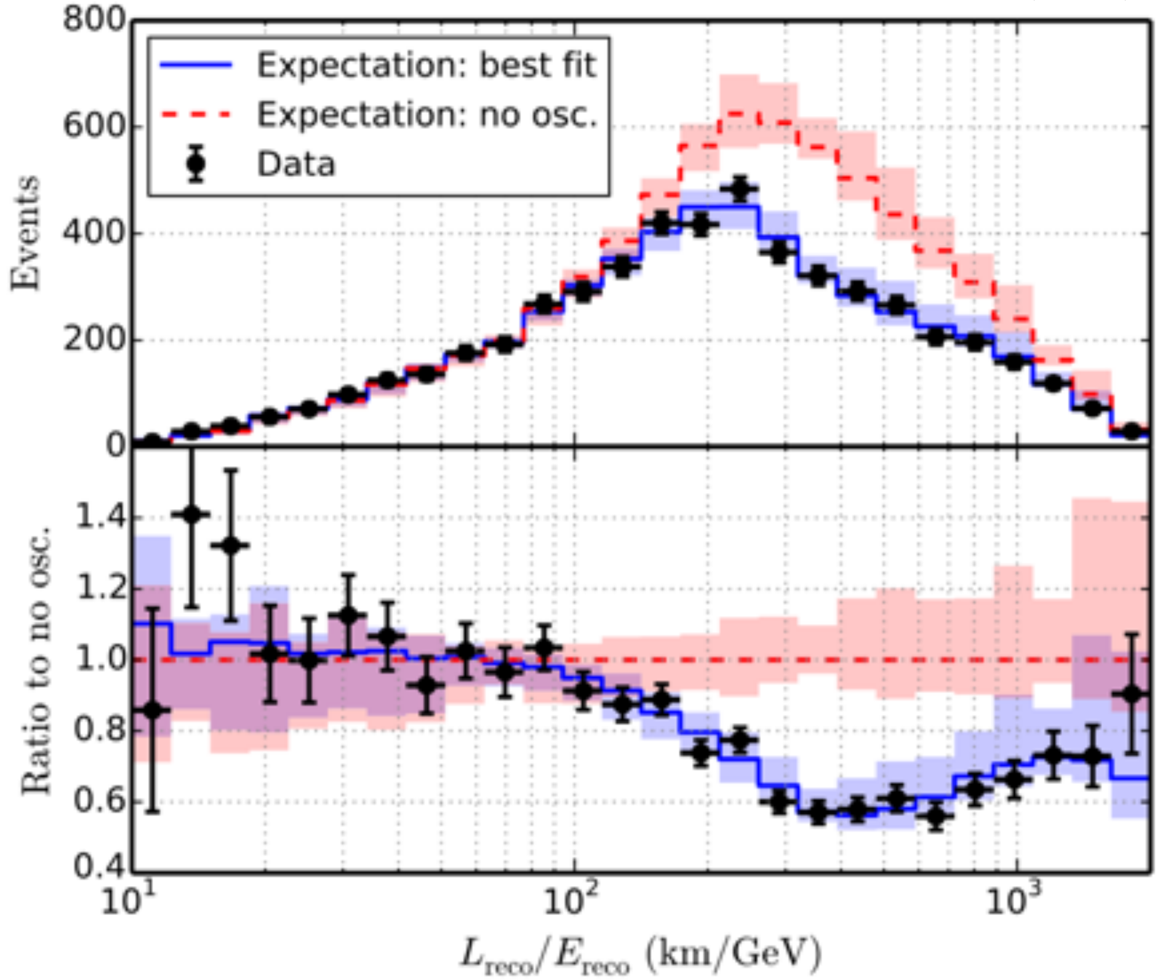




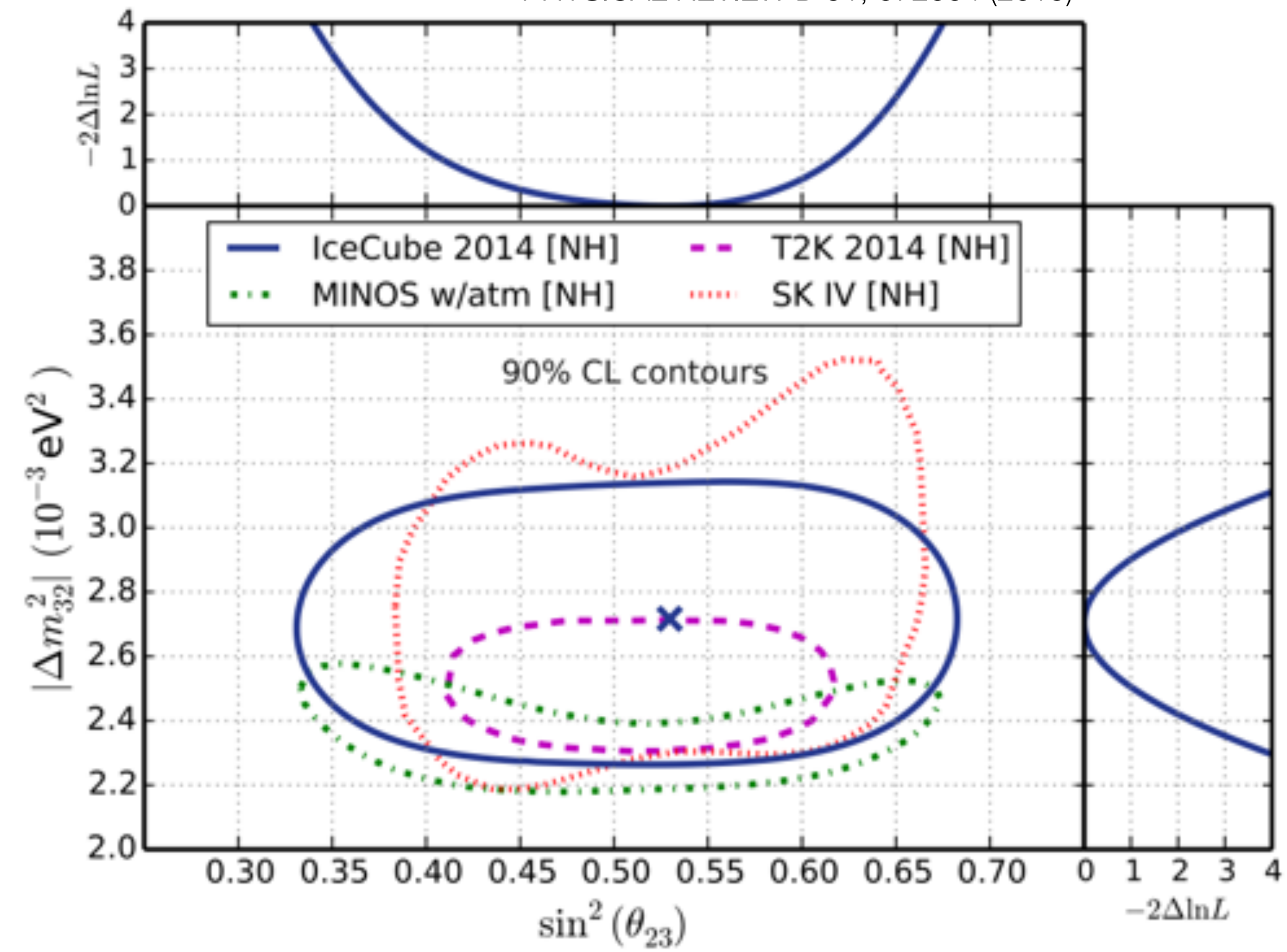
Atmospheric neutrinos in IceCube/Deep Core

IceCube	D = 125 m
DeepCore	D = 75 m
PINGU (proposed)	D = 20 m

Interesting range for
matter effects and mass
ordering sensitivity



PHYSICAL REVIEW D 91, 072004 (2015)



Atmospheric neutrinos in IceCube/Deep Core

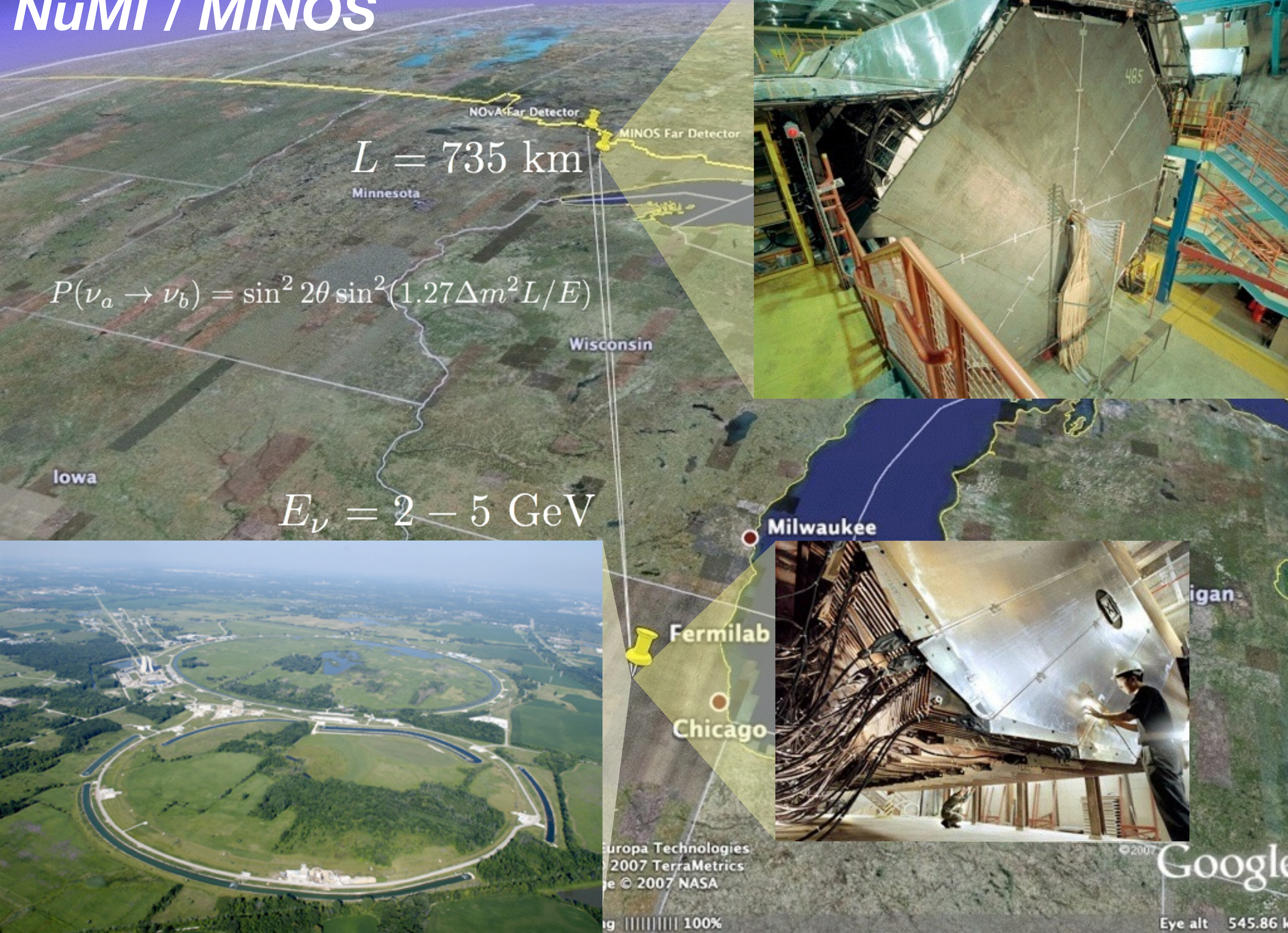
IceCube	D = 125 m
DeepCore	D = 75 m
PINGU (proposed)	D = 20 m

NuMI / MINOS

$$L = 735\ \mathrm{km}$$

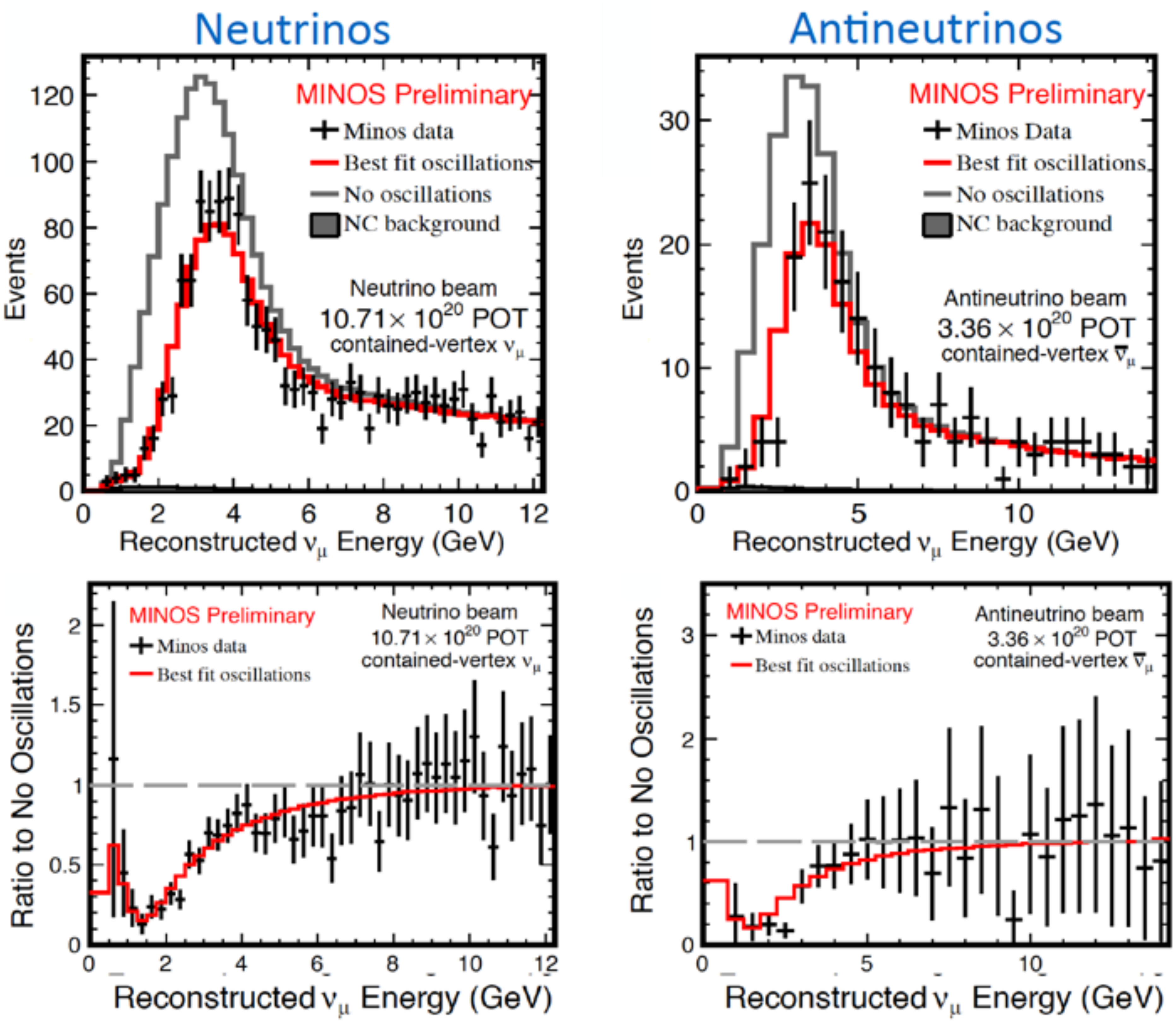
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

$$E_\nu = 2 - 5\ \mathrm{GeV}$$



MINOS

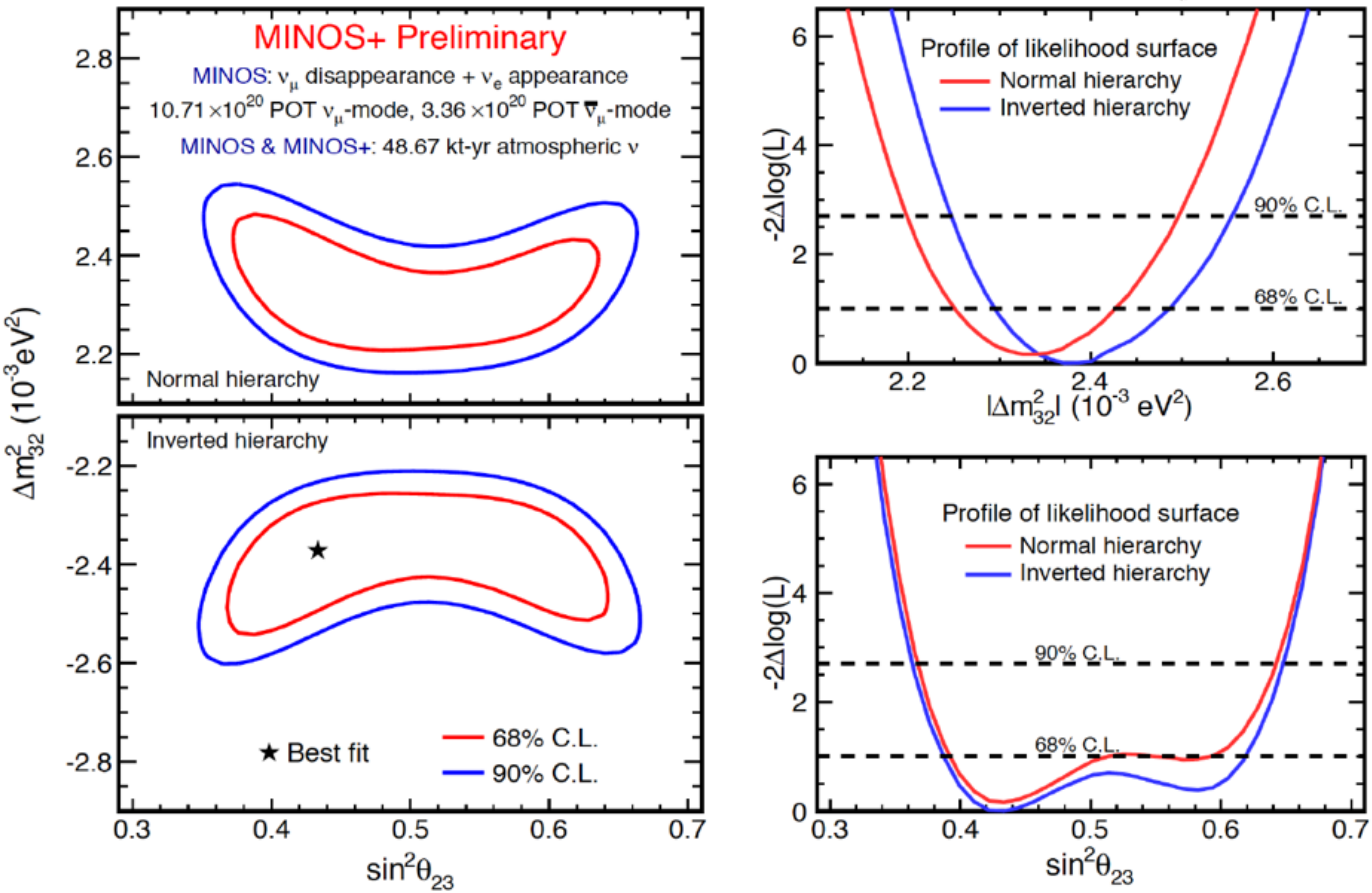
$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$



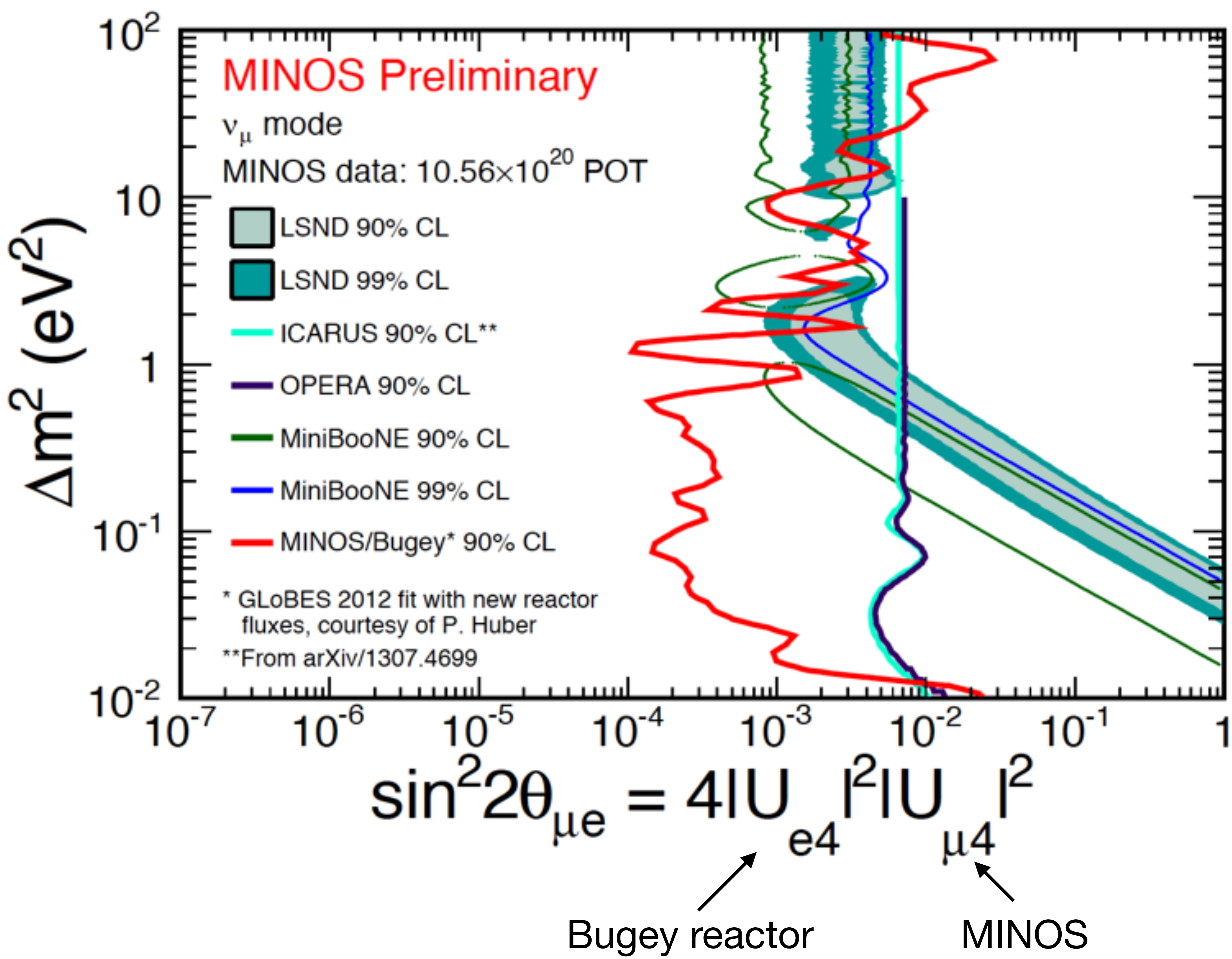
$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

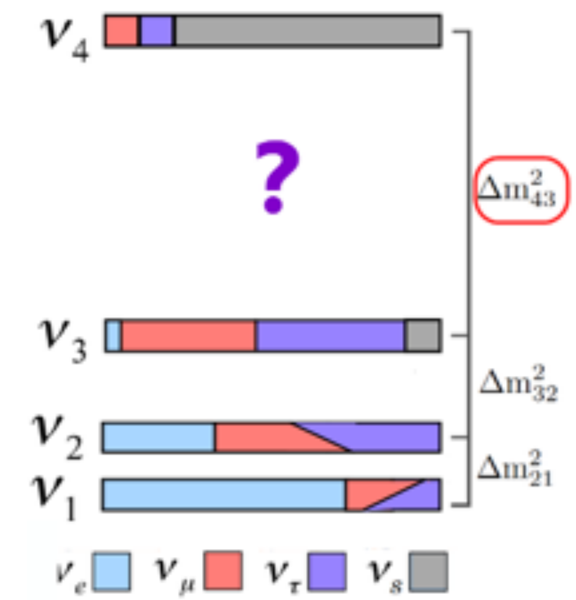
backgrounds	69.1	10.5
“nominal” signal at θ	+26.0	+3.1
total:	**95.1**	**13.6**
Observed	**88**	**12**

MINOS$^{(+)}$
Combined fit to beam and atmospheric neutrinos

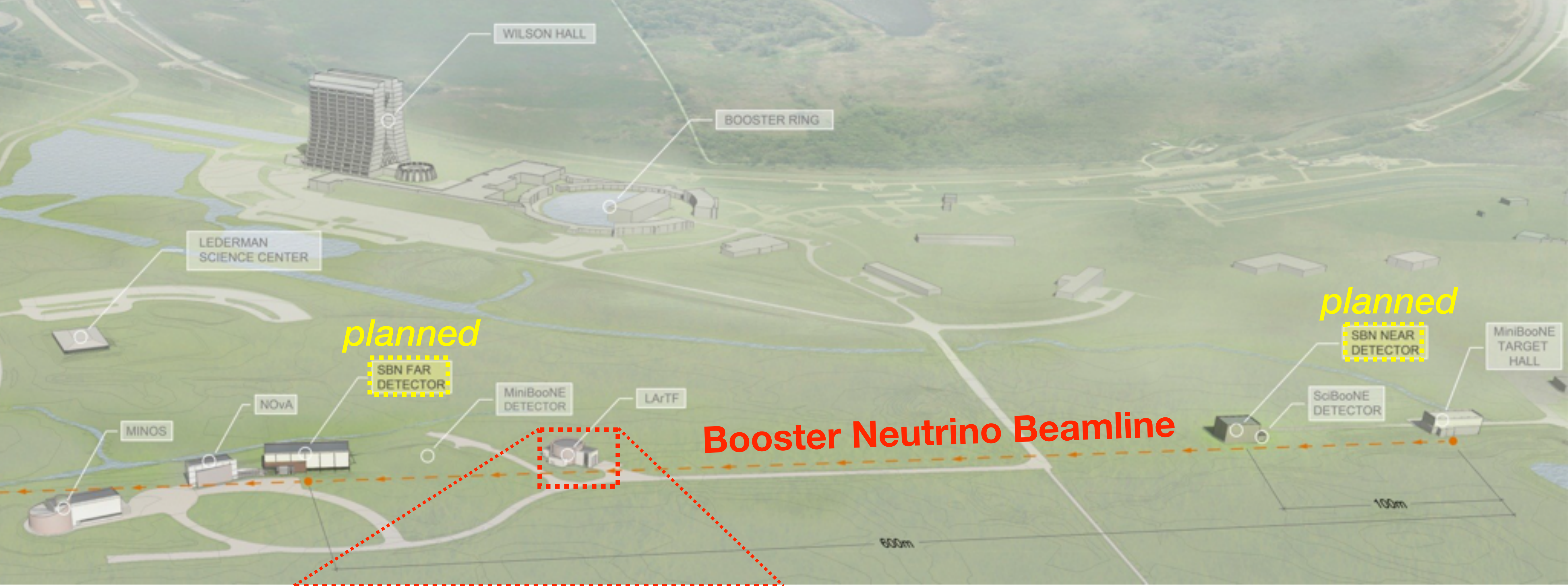


MINOS
Fit to sterile neutrino oscillations in 3+1 model





Use 3+1 model to relate MINOS and Bugey limits on active neutrino disappearance to the rate of $\nu_\mu \rightarrow \nu_e$ at short baseline

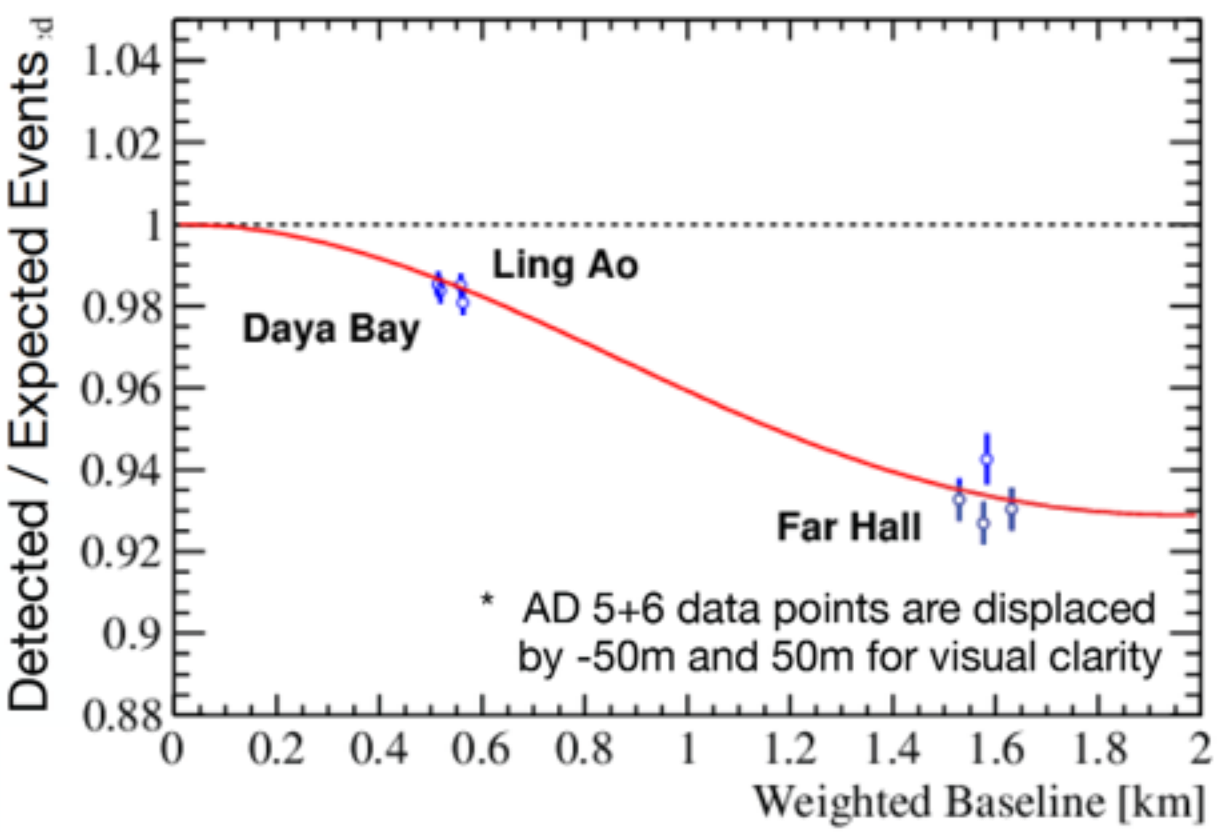


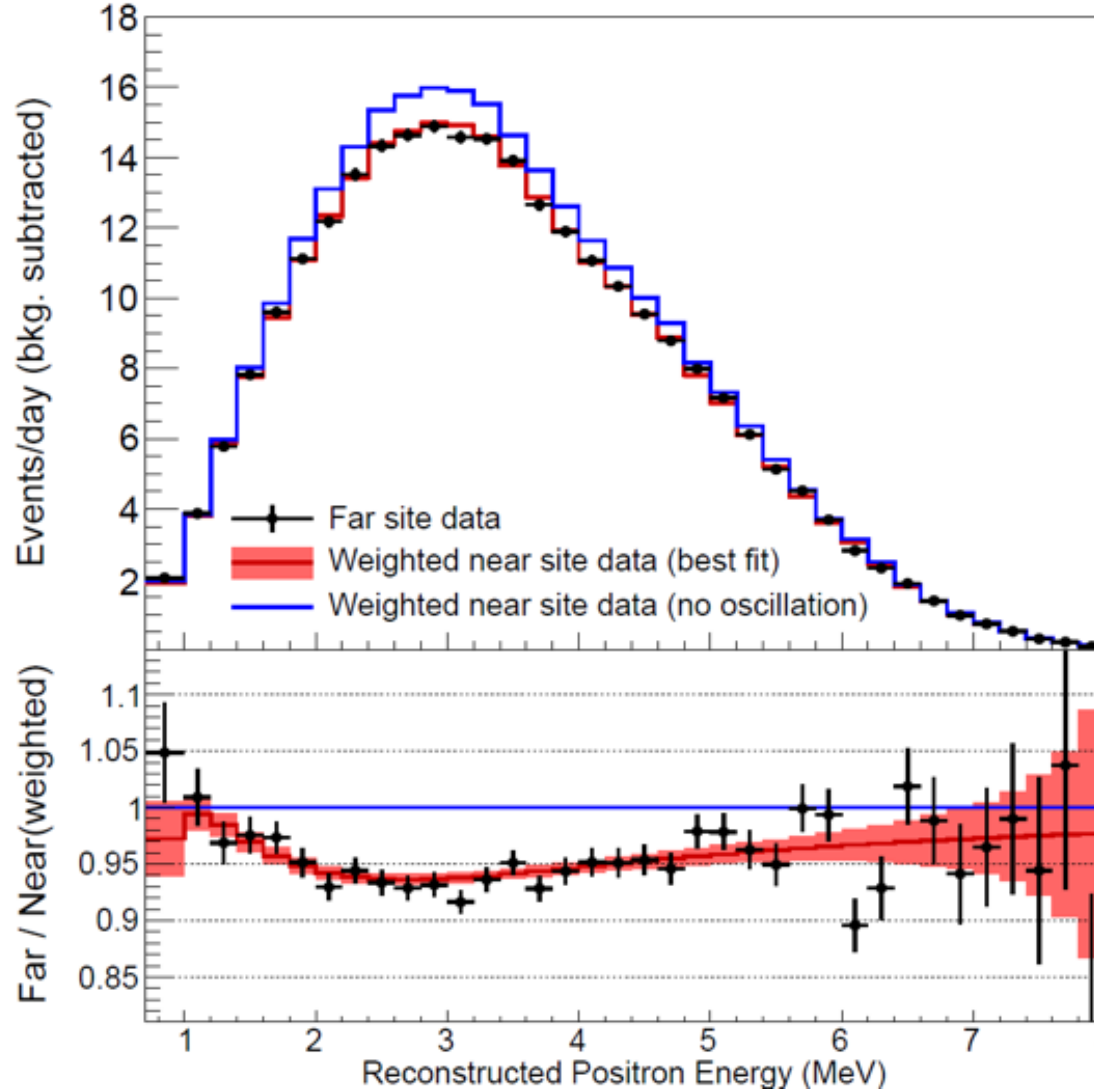
MicroBooNE installed,
cooling down
Starts data taking this year

Short baseline neutrino physics on the Fermilab Booster Neutrino Beam

Searching for sterile neutrinos while advancing liquid argon TPCs

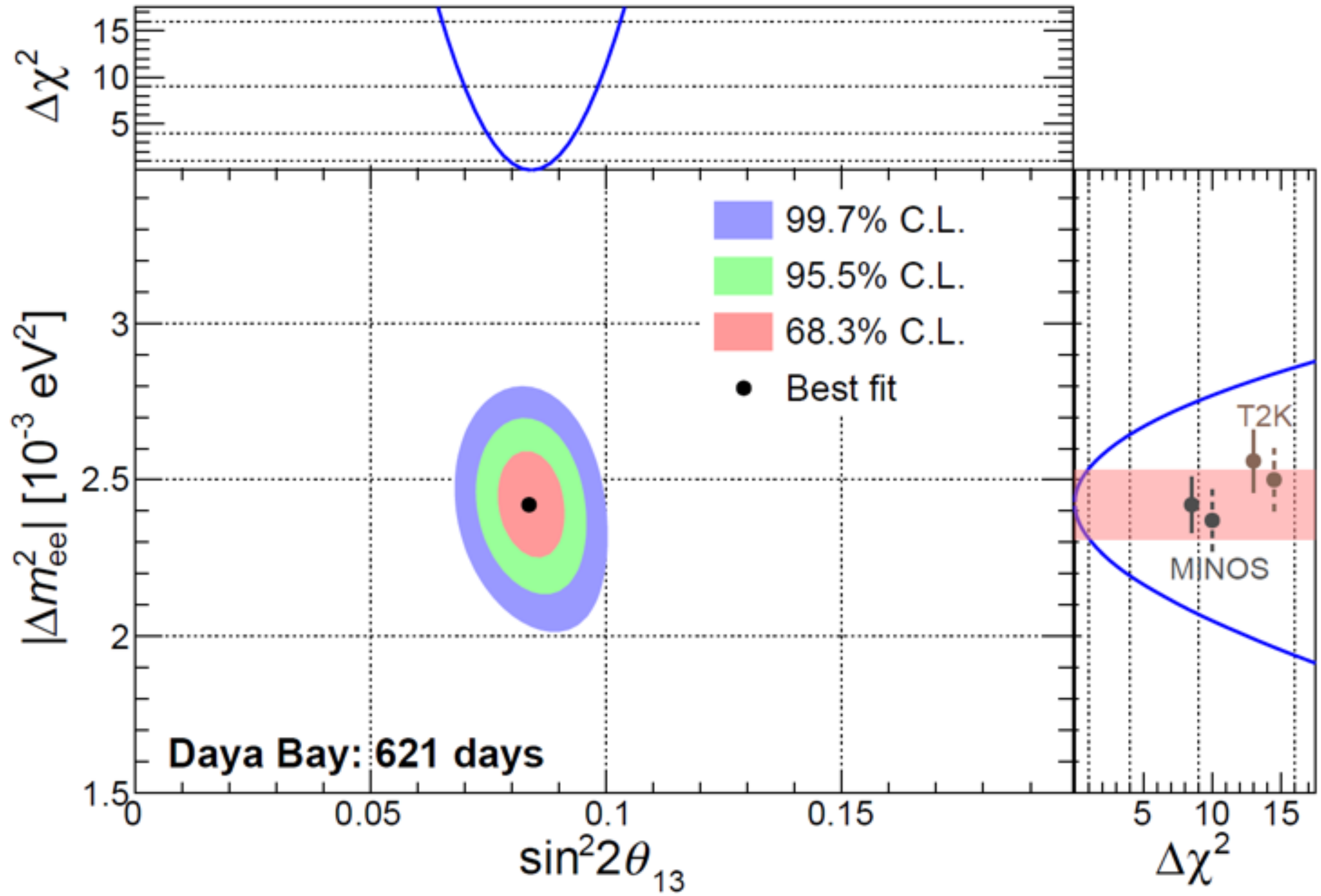
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{\text{atm}}\frac{L}{4E}) - \sin^2(2\theta_{12})\cos^4(\theta_{13})\sin^2(\Delta m^2_{\text{sol}}\frac{L}{4E})$$





Daya Bay Reactor Antineutrino experiment

Disappearance of electron antineutrinos provides clean measurement of θ_{13}



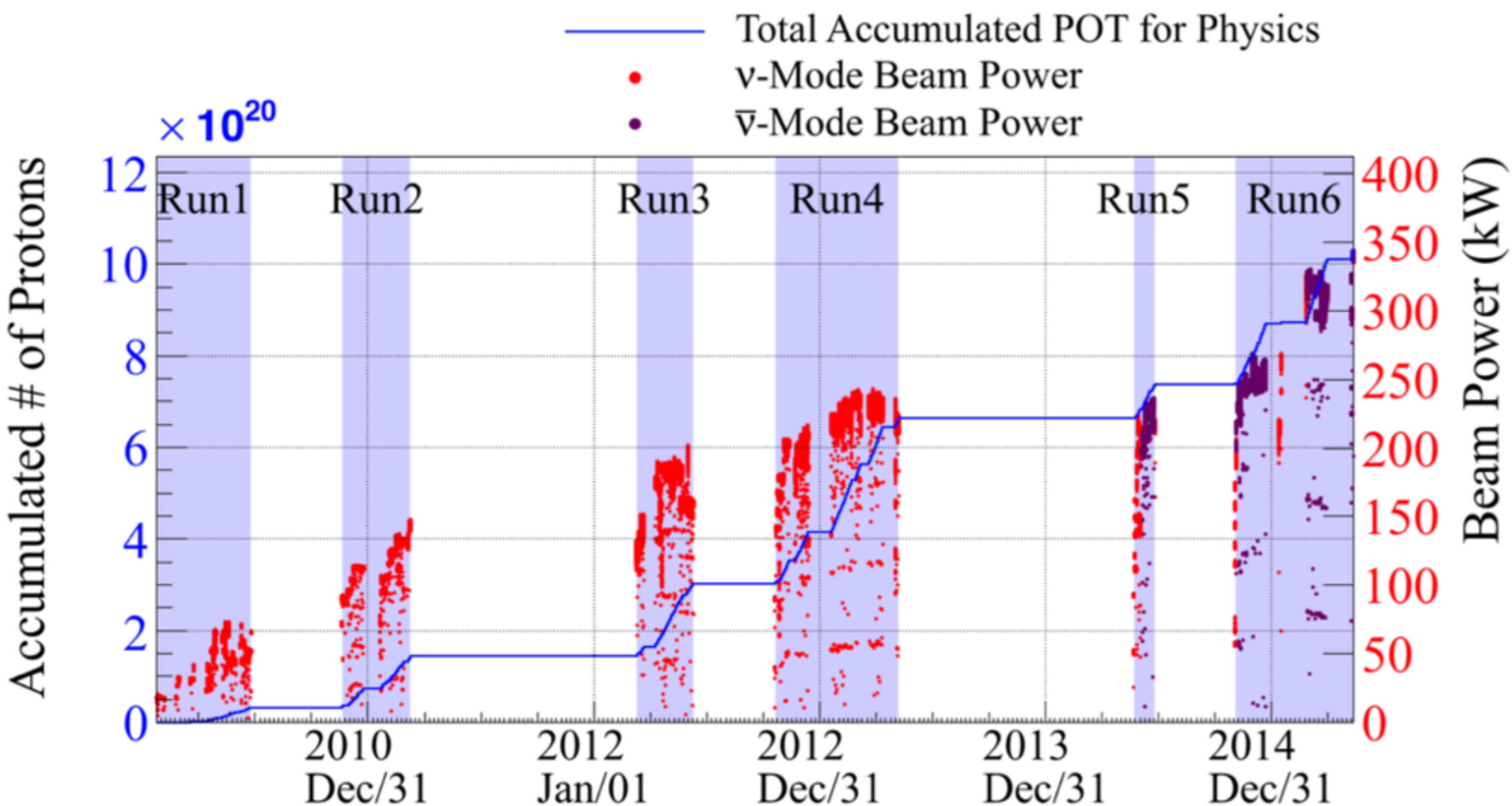
Double Chooz	0.090 ± 0.030
RENO	0.088 ± 0.011
Daya Bay	0.084 ± 0.005
Combined	0.0848 ± 0.0045

Daya Bay Reactor Antineutrino experiment

θ_{13} is now best know mixing angle

T2K Experiment

T2K Beam delivery

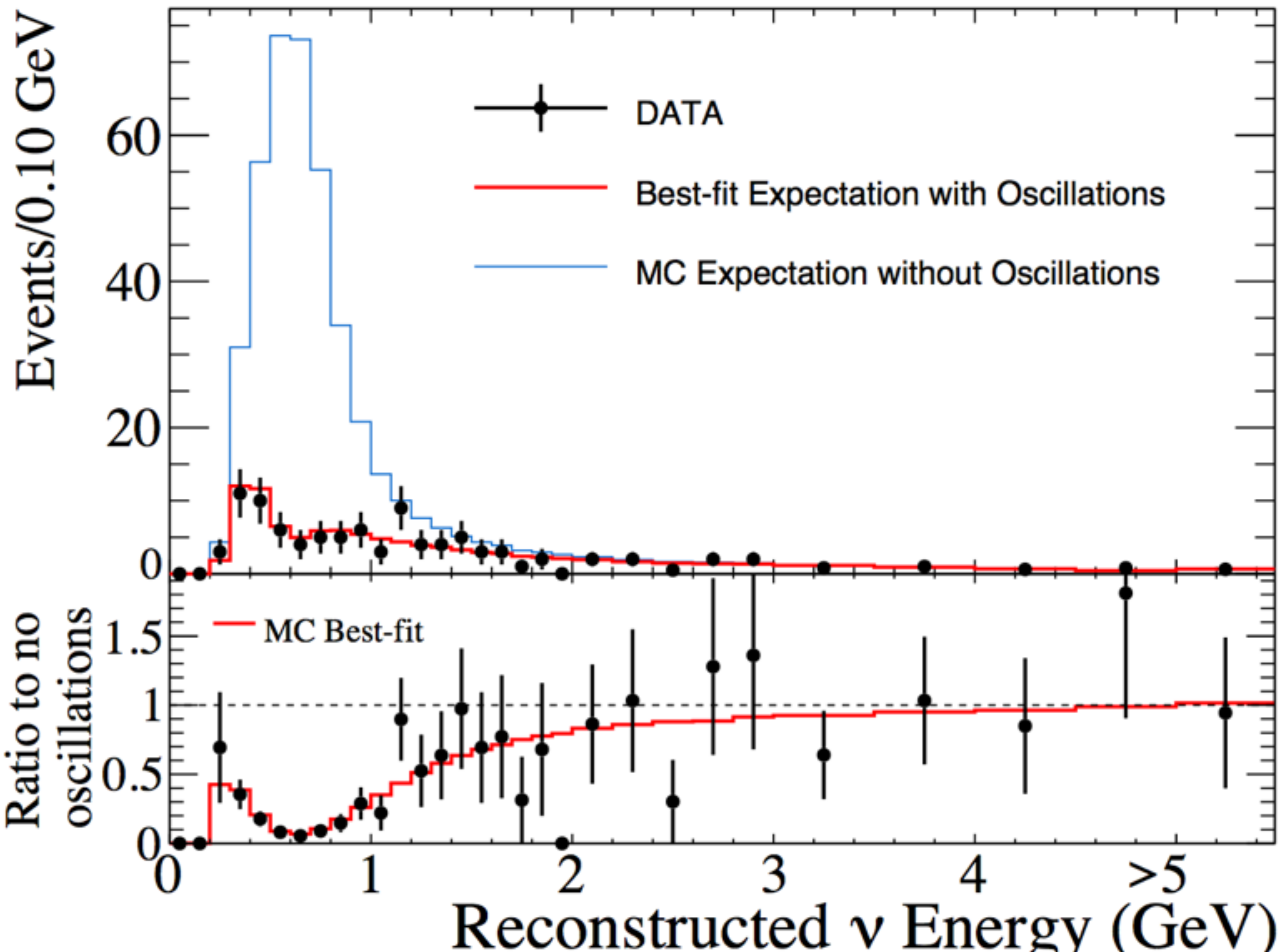


neutrinos: 6.9×10^{20} POT

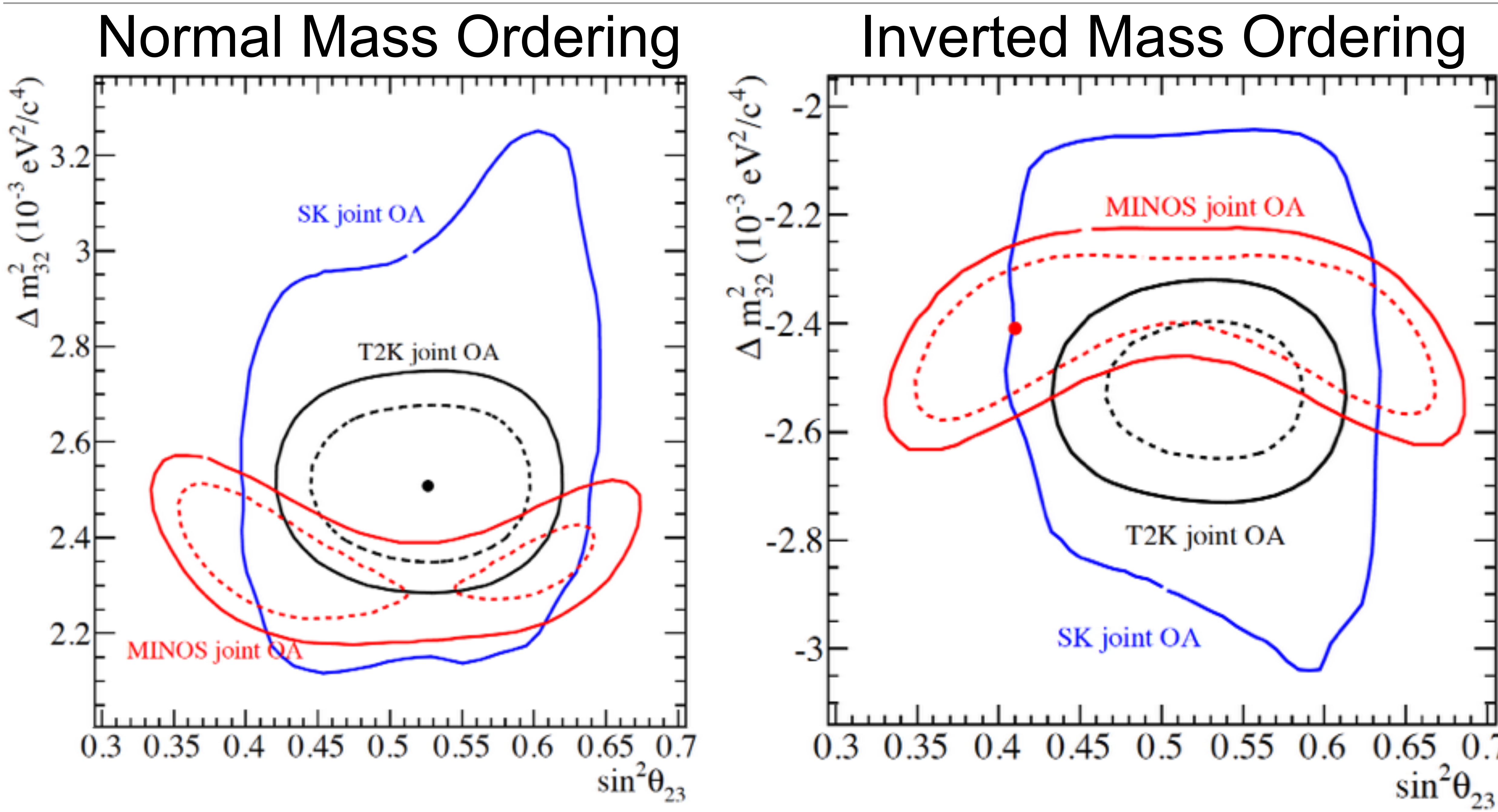
anti-neutrinos: 4.0×10^{20} POT

Total: 10.9×10^{20} POT

T2K
ν_μ charged-current spectra



T2K
$\sin^2\theta_{23}$ result

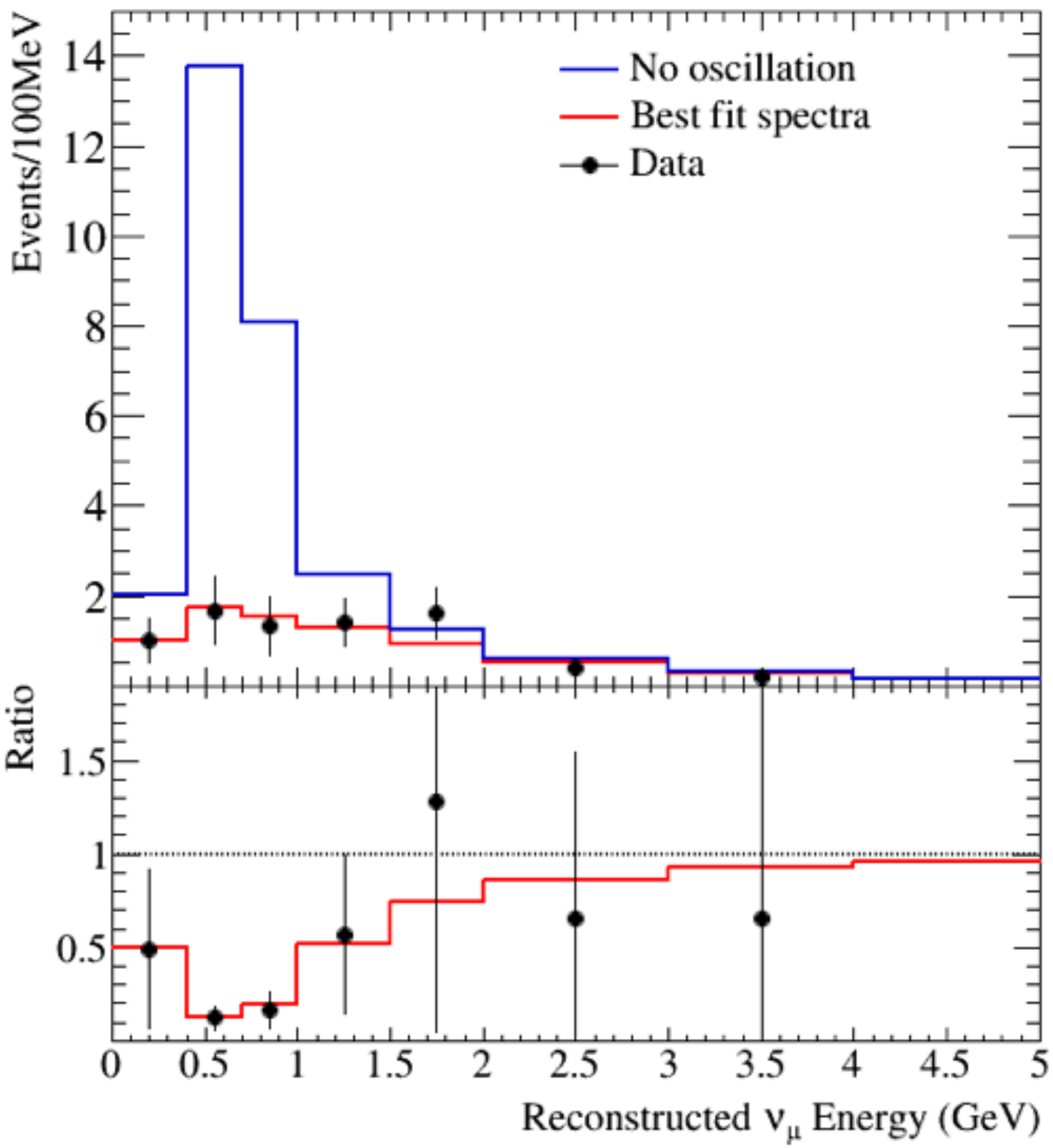


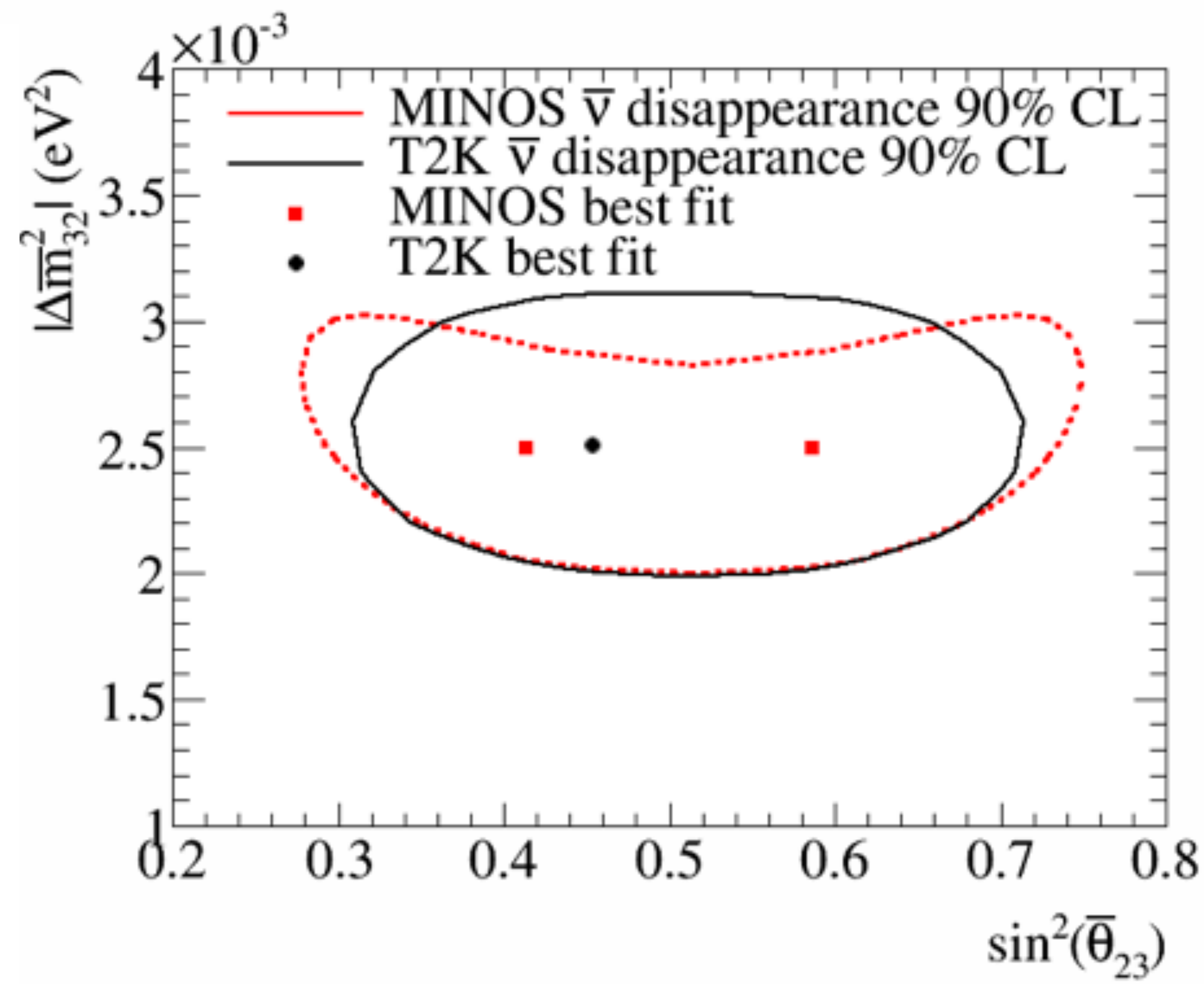
Normal hierarchy: $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

Inverted hierarchy: $\sin^2\theta_{23} = 0.511 \pm 0.055$

arXiv:1502.01550v2

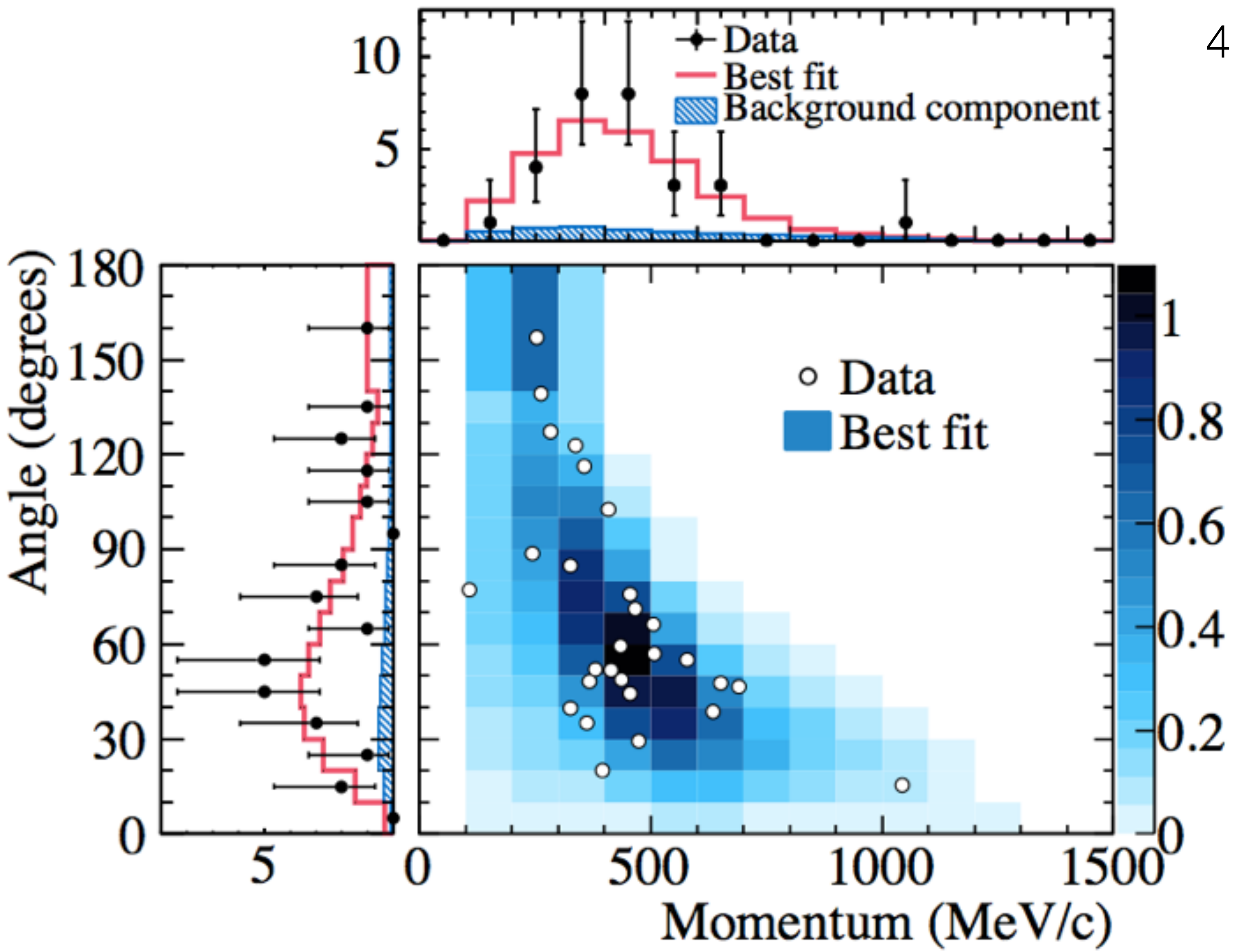
T2K Antineutrino Results





Also sees 3 e-like events on background of 1.8 in antineutrino running

T2K
Electron neutrino signal events



4.92 ± 0.55 background
28 events observed
7.3σ observation

21.6 events expected
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$
$\sin^2\theta_{23} = 0.5$

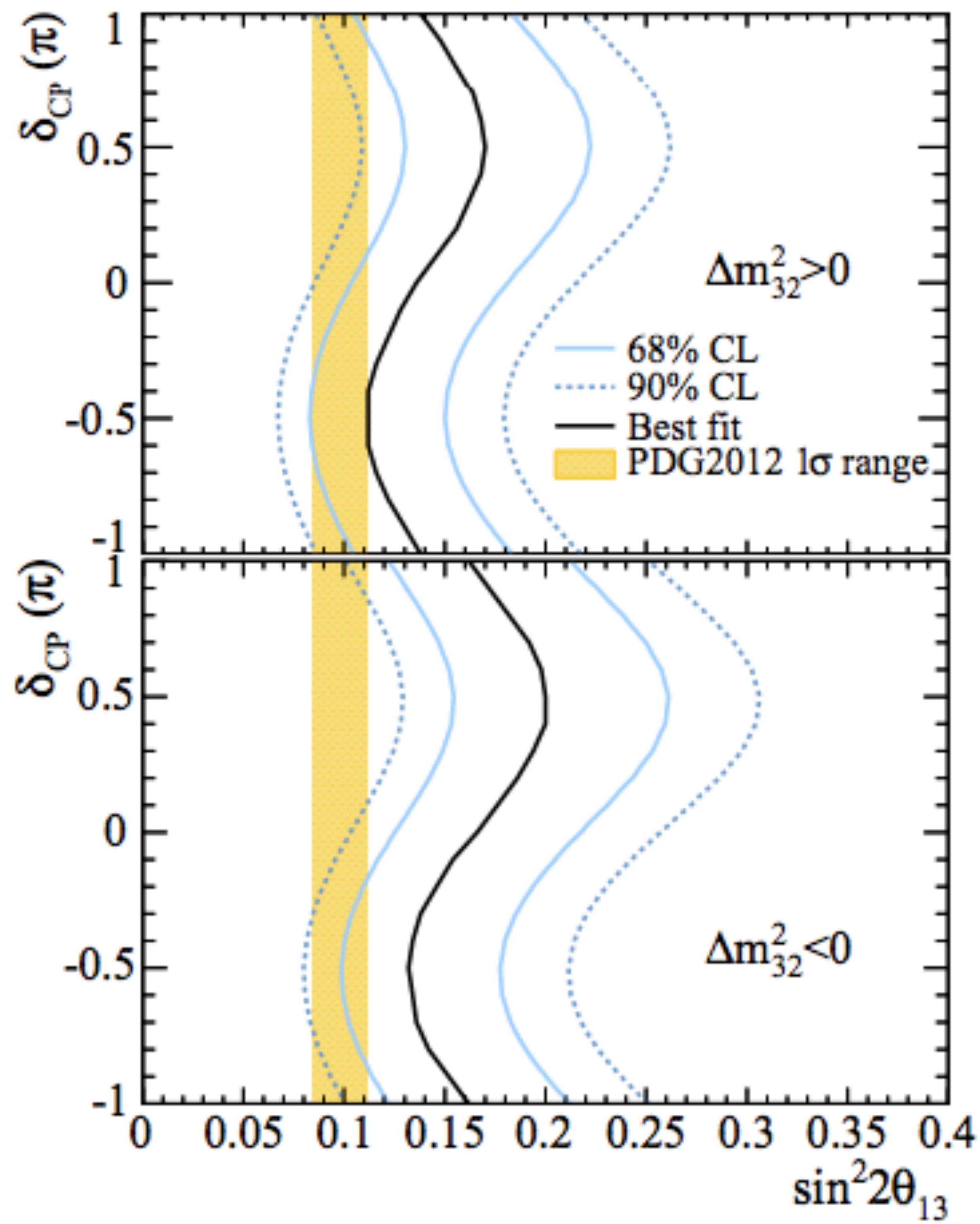
Comparing T2K results with reactors

T2K $\sin^2 2\theta_{13}$ result computed assuming $\sin^2\theta_{23}$=0.5, δ_{CP}=0, and normal hierarchy (top), and inverted hierarchy (bottom)

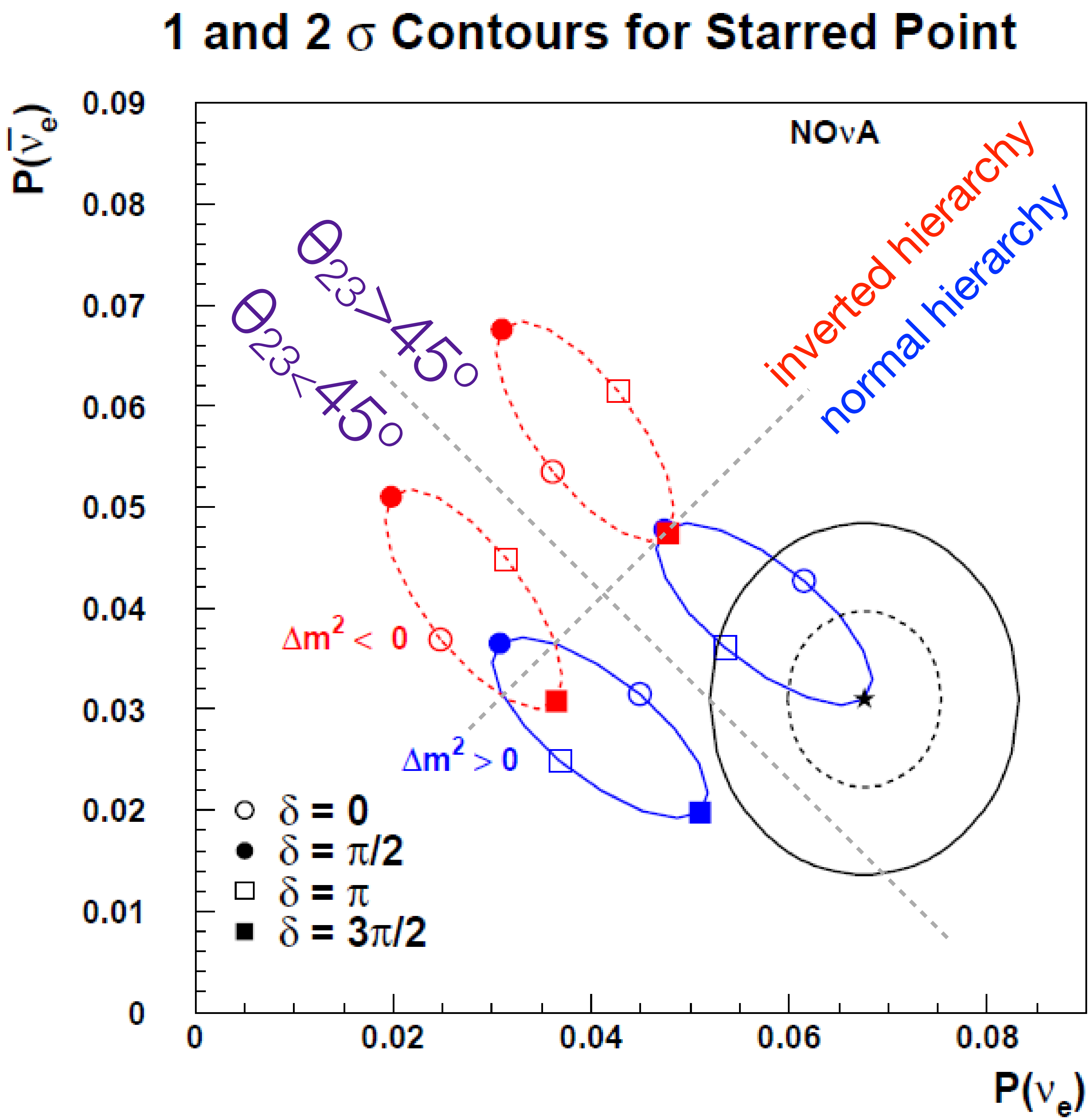
Consistent at 90% CL (1.6σ)

…but excess seen by T2K nudges all remaining unknowns in direction to increase rates

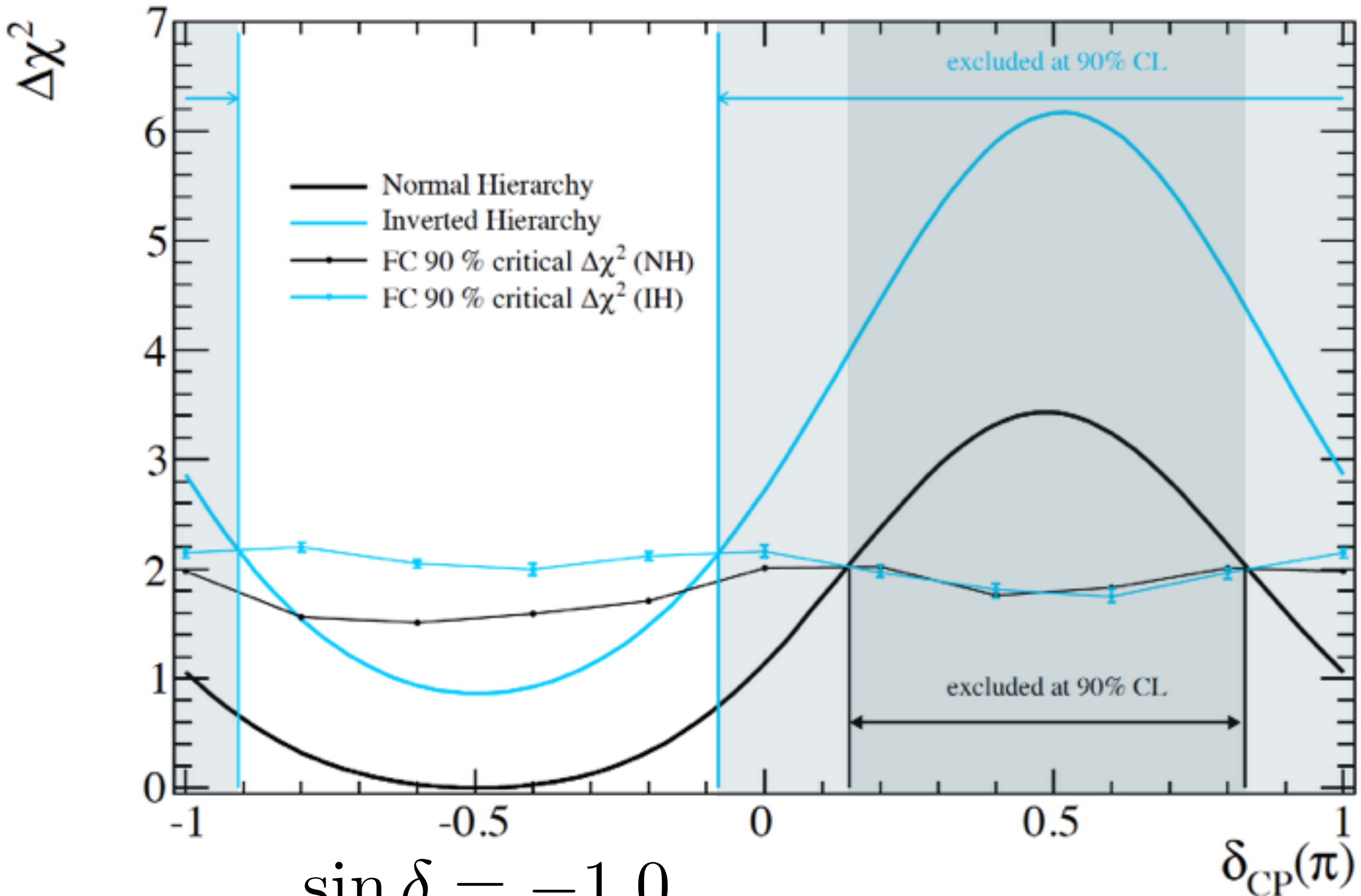
- normal hierarchy
- θ_{23}>45°
- δ_{CP}=-π/2 (aka 3π/2)



Borrowing an illustration from the NOvA experiment



Combining T2K with Reactors



$\sin\delta = -1.0$

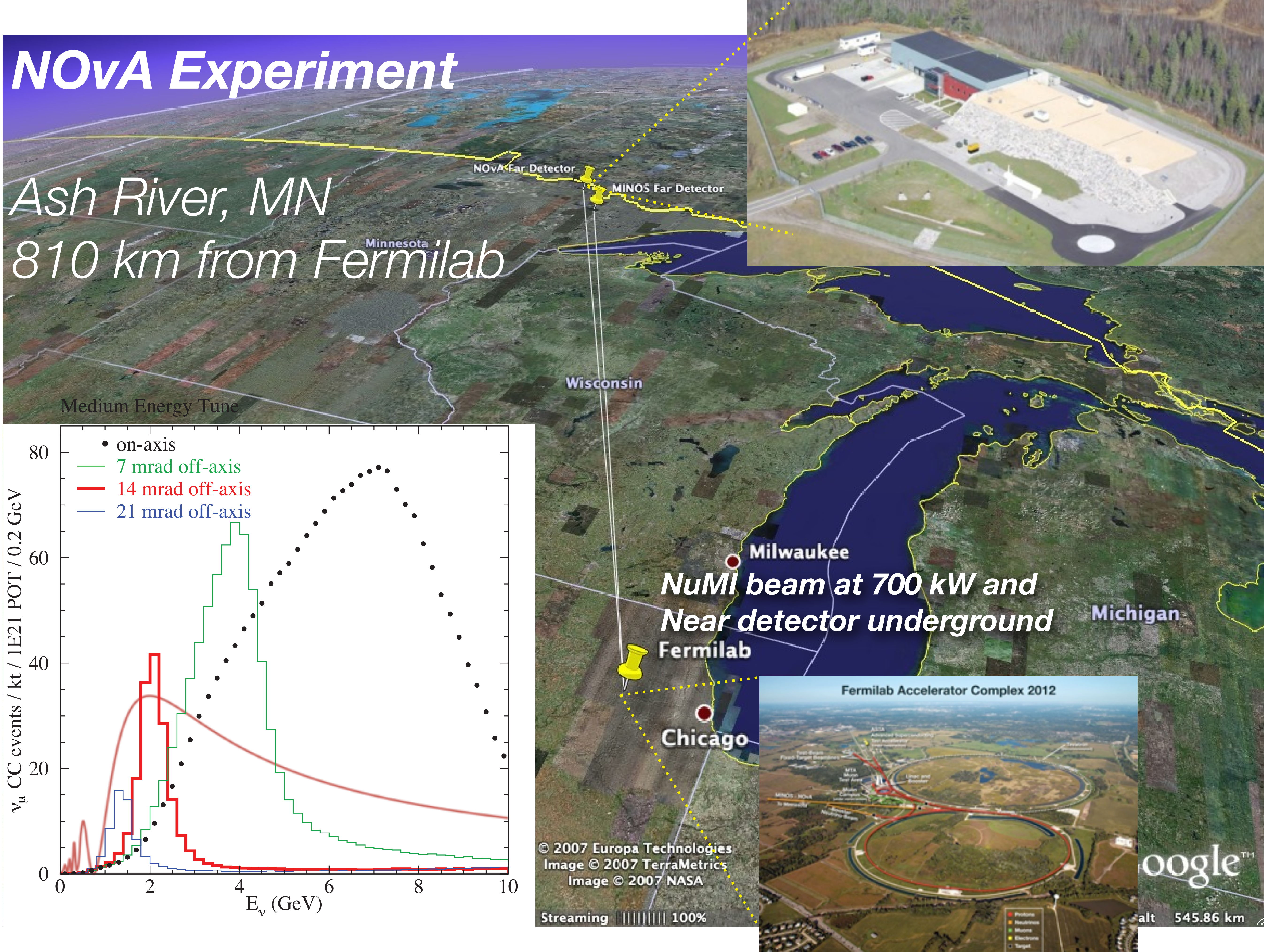
The tension with reactors gives some early sensitivity to δ_{CP}

T2K data prefers the normal hierarchy with $\delta_{CP}<0$ at ~90% C.L.

NOvA Experiment

Ash River, MN
810 km from Fermilab

NuMI beam at 700 kW and Near detector underground

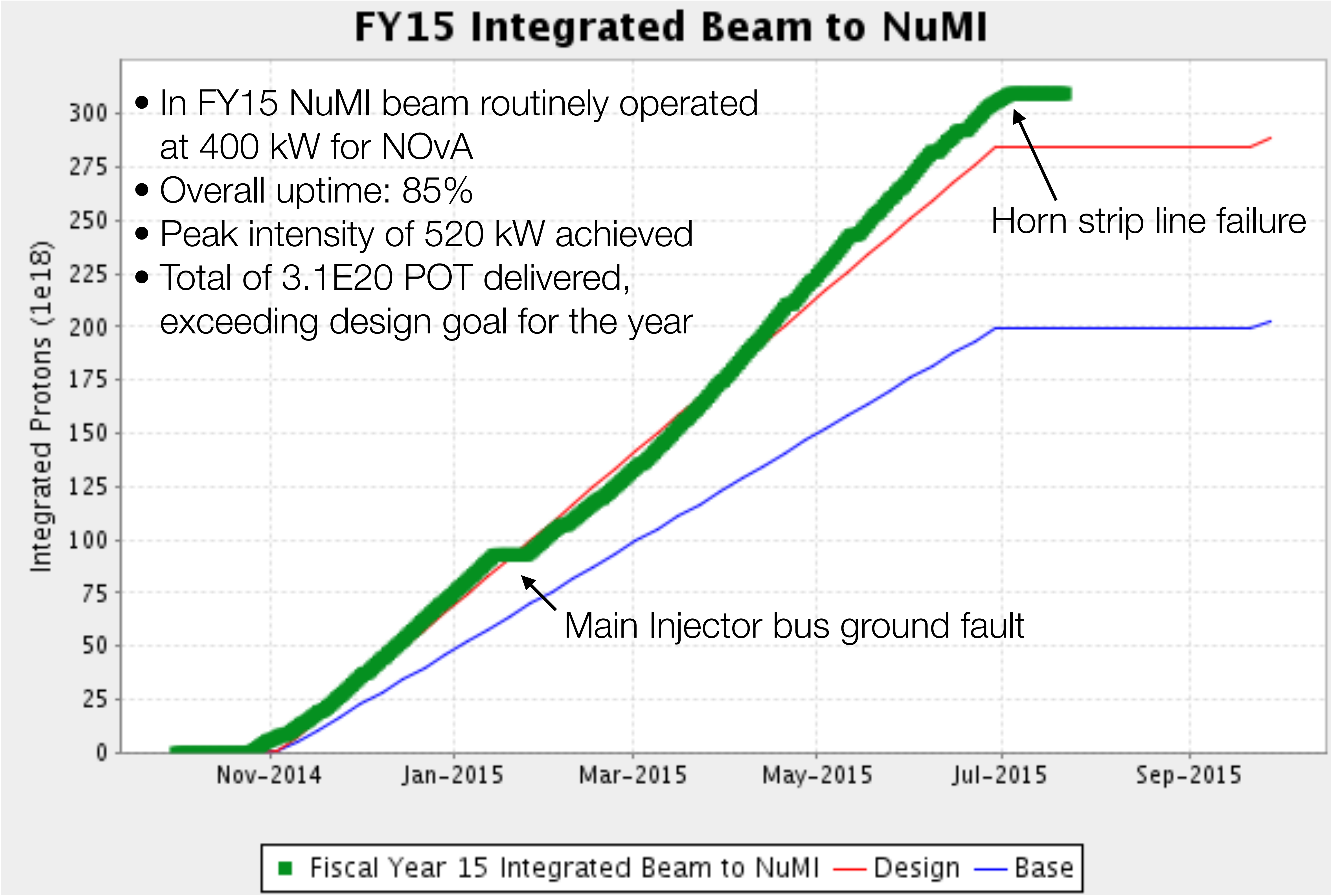


Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics parameters

Factor	Type	Inverts for $\overline{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	+/-10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the ±2σ range found by a recent global fit (PRD 90, 093006)

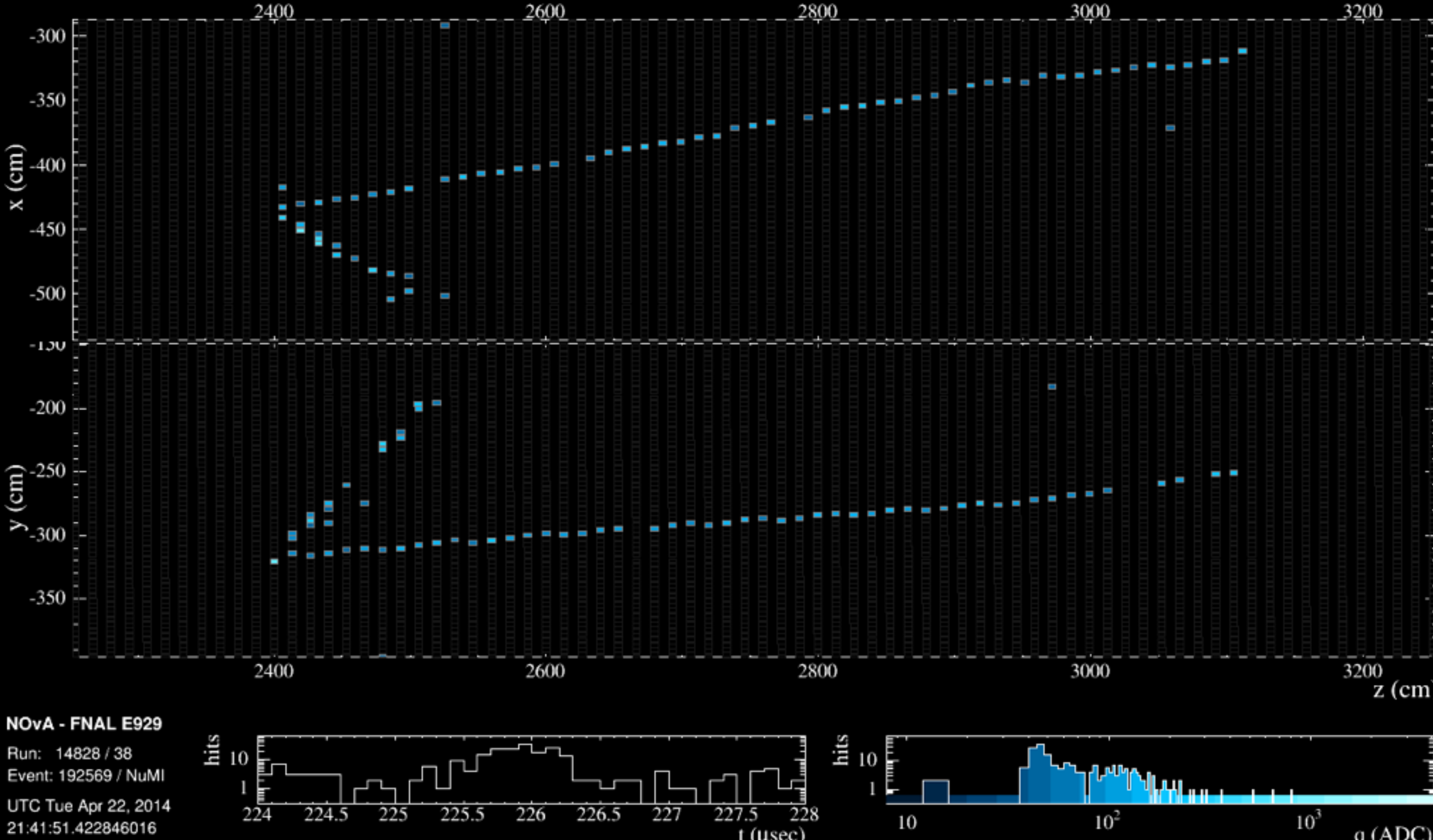


US FY2015 NuMI Beam Performance

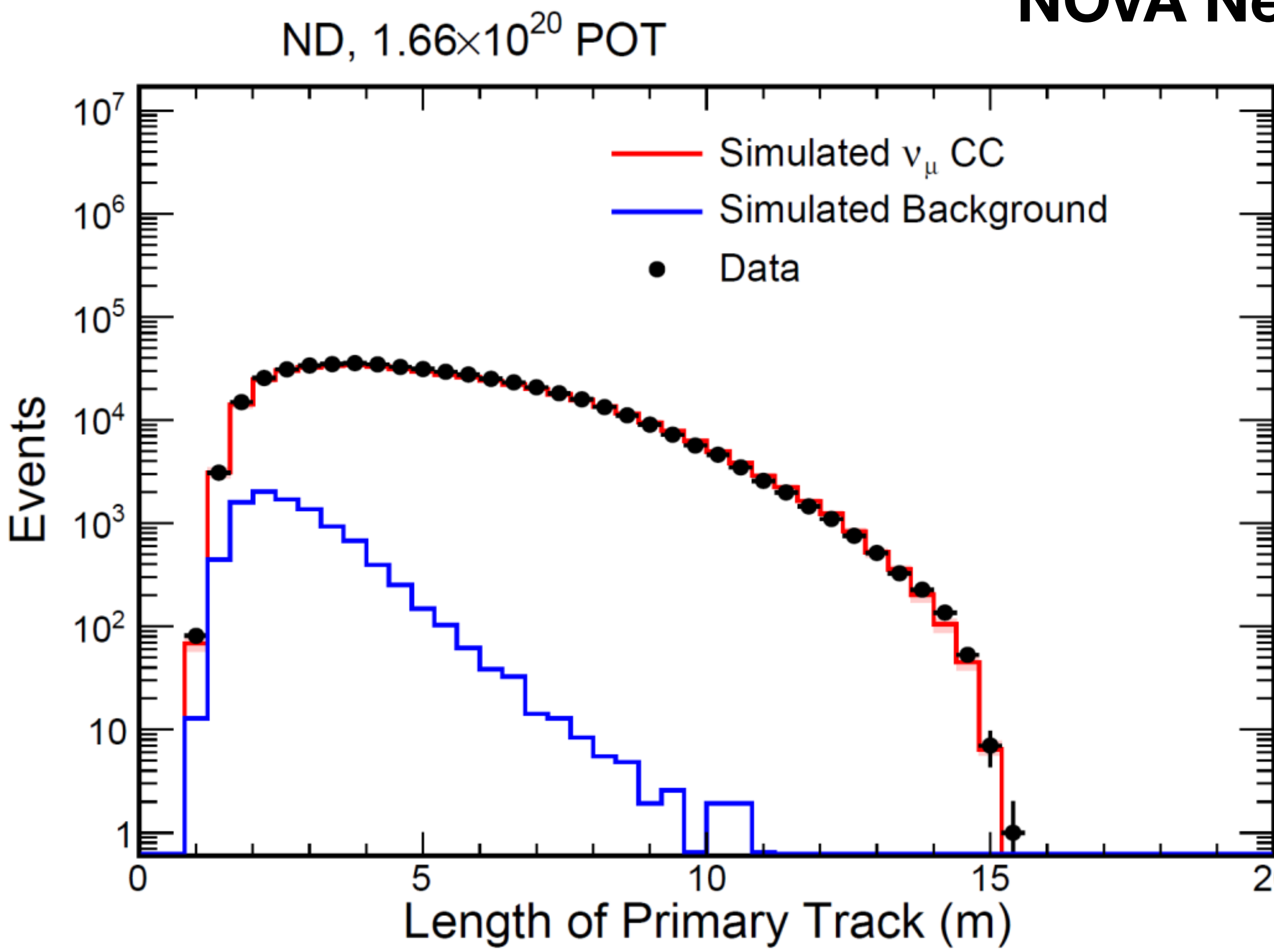
NOvA Far Detector

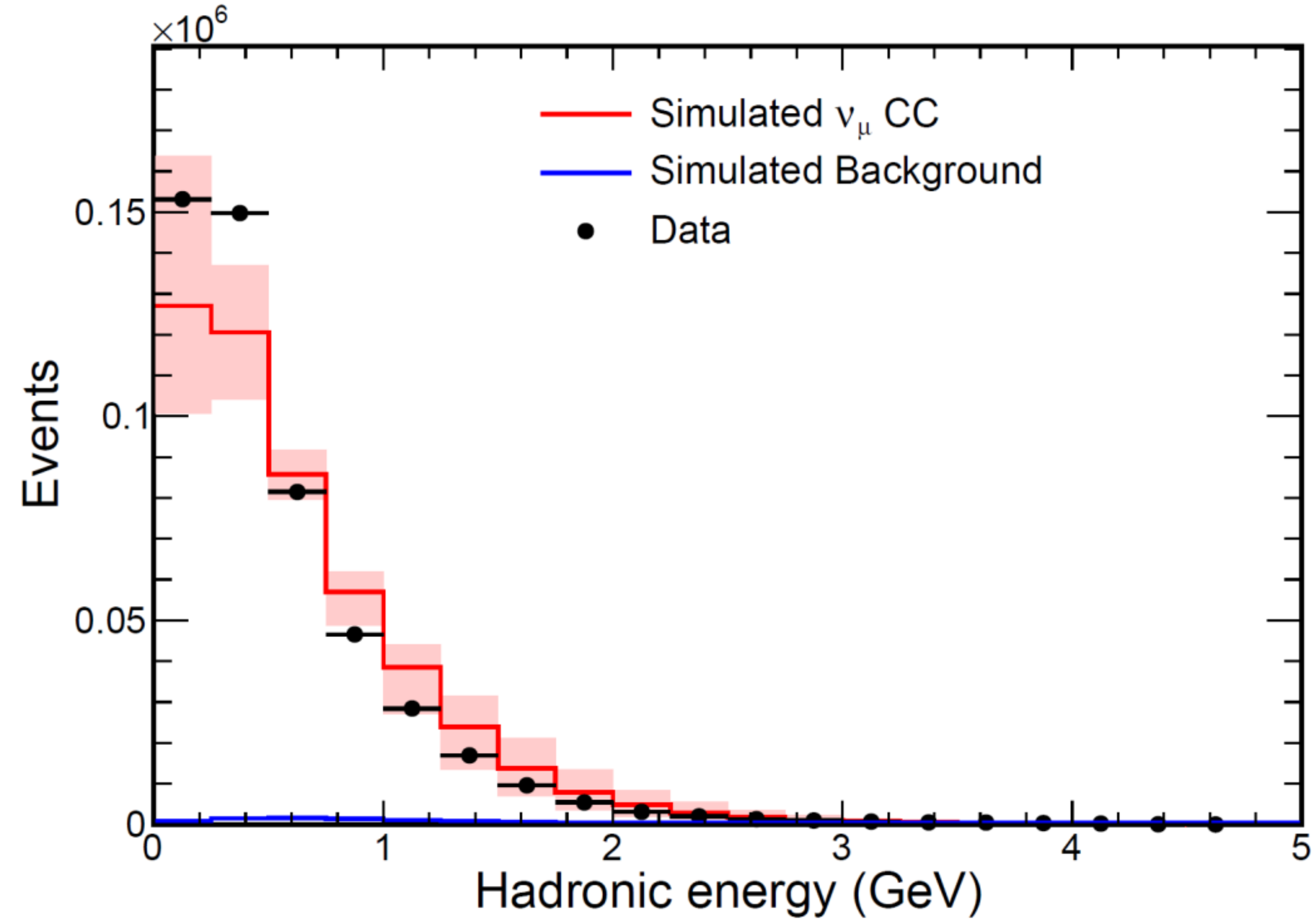
NOvA Far Detector completed in July 2014
On time, under budget!
Running with >99% active channels and >95% uptime
Reporting first results today

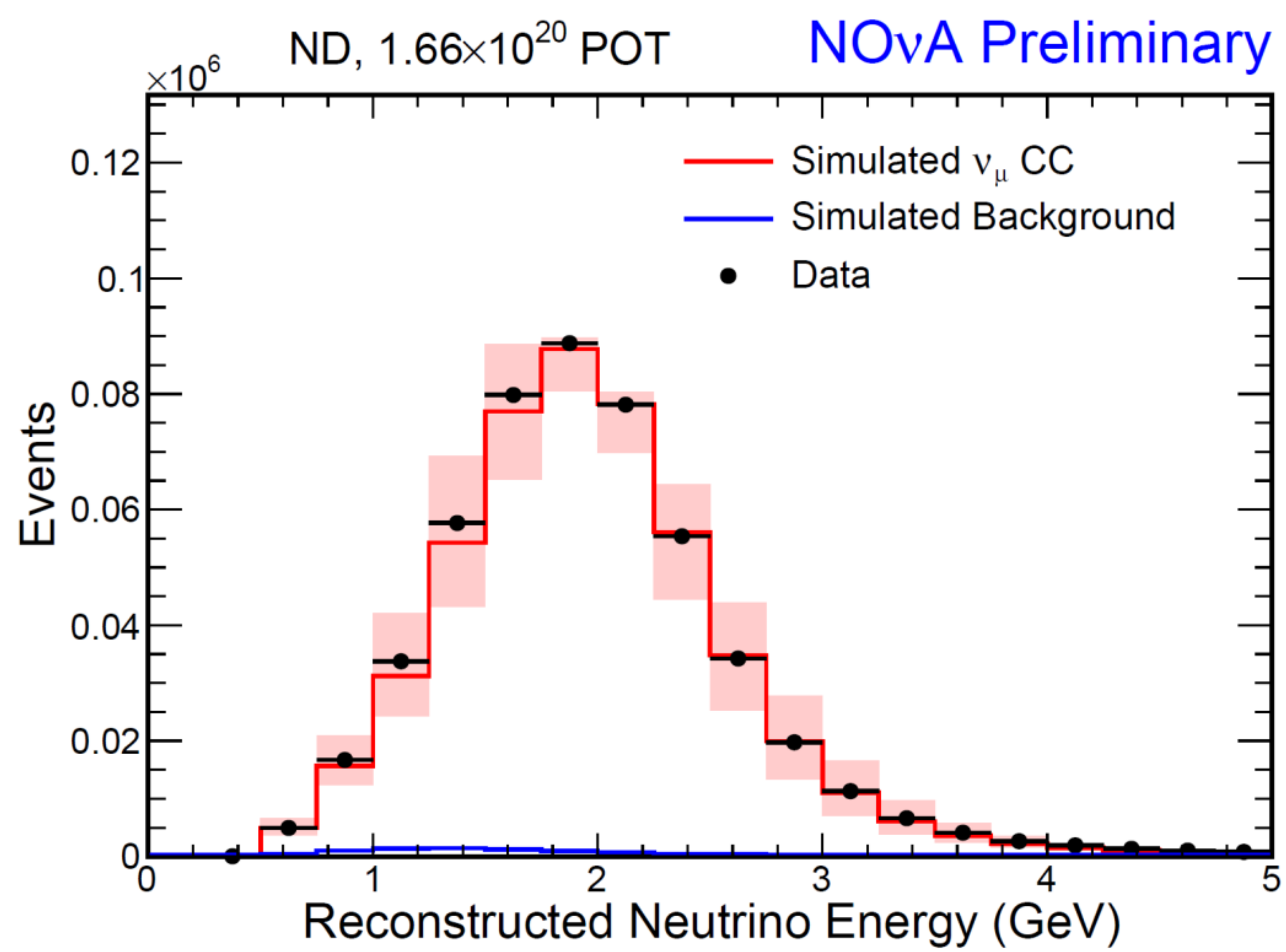
NOvA ν_μ Charged-current candidate



NOvA Near Detector



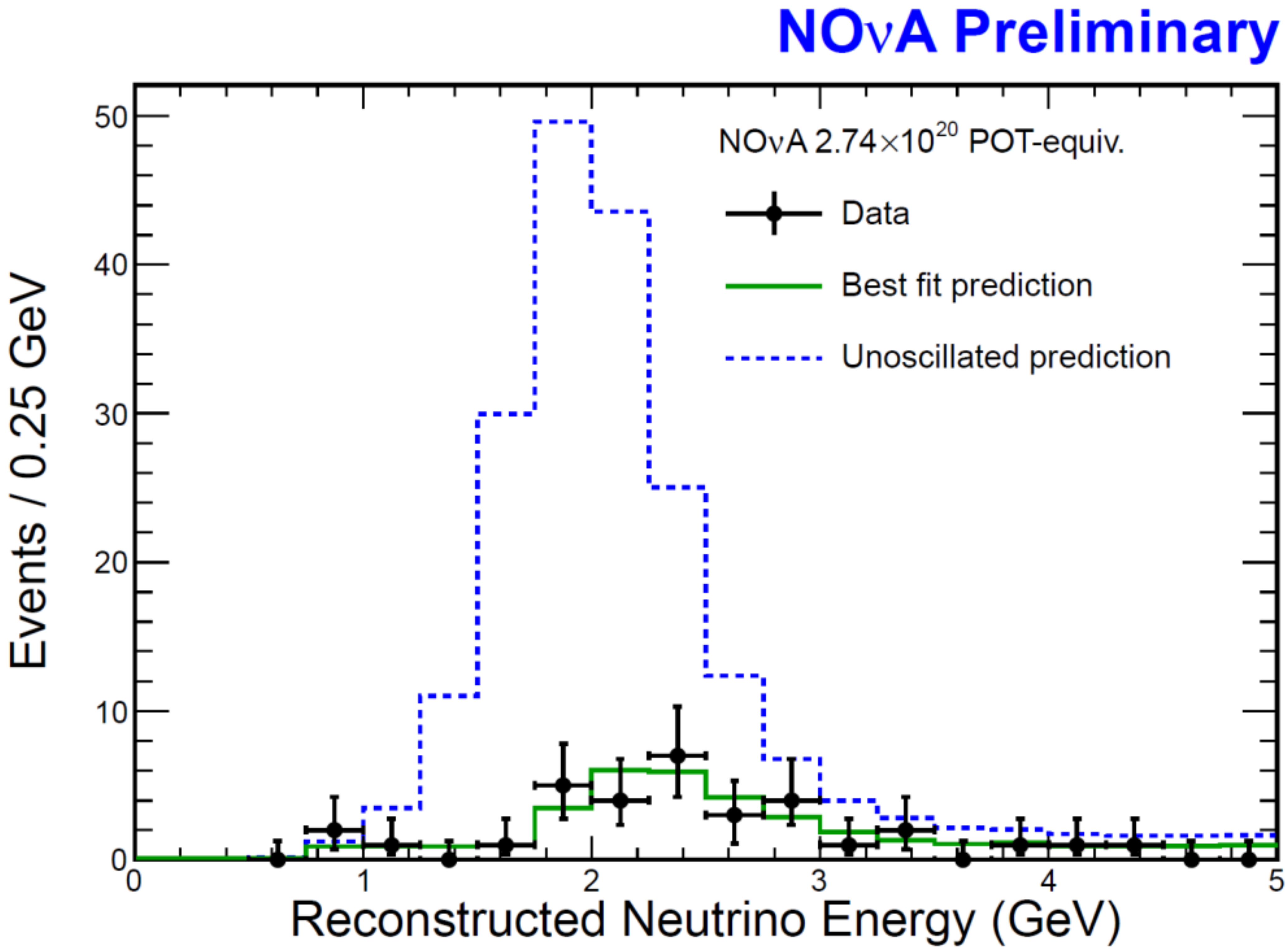




NOvA Neutrino Energy Reconstruction

$$E_\nu = E_\mu + E_{\mathrm{hadrons}}$$

- Muon variables agree well
- Monte Carlo puts 21% more energy into hadron system than seen in data
- Results in 6% overall neutrino energy scale uncertainty
- Data from NOvA and MINERvA should help with this



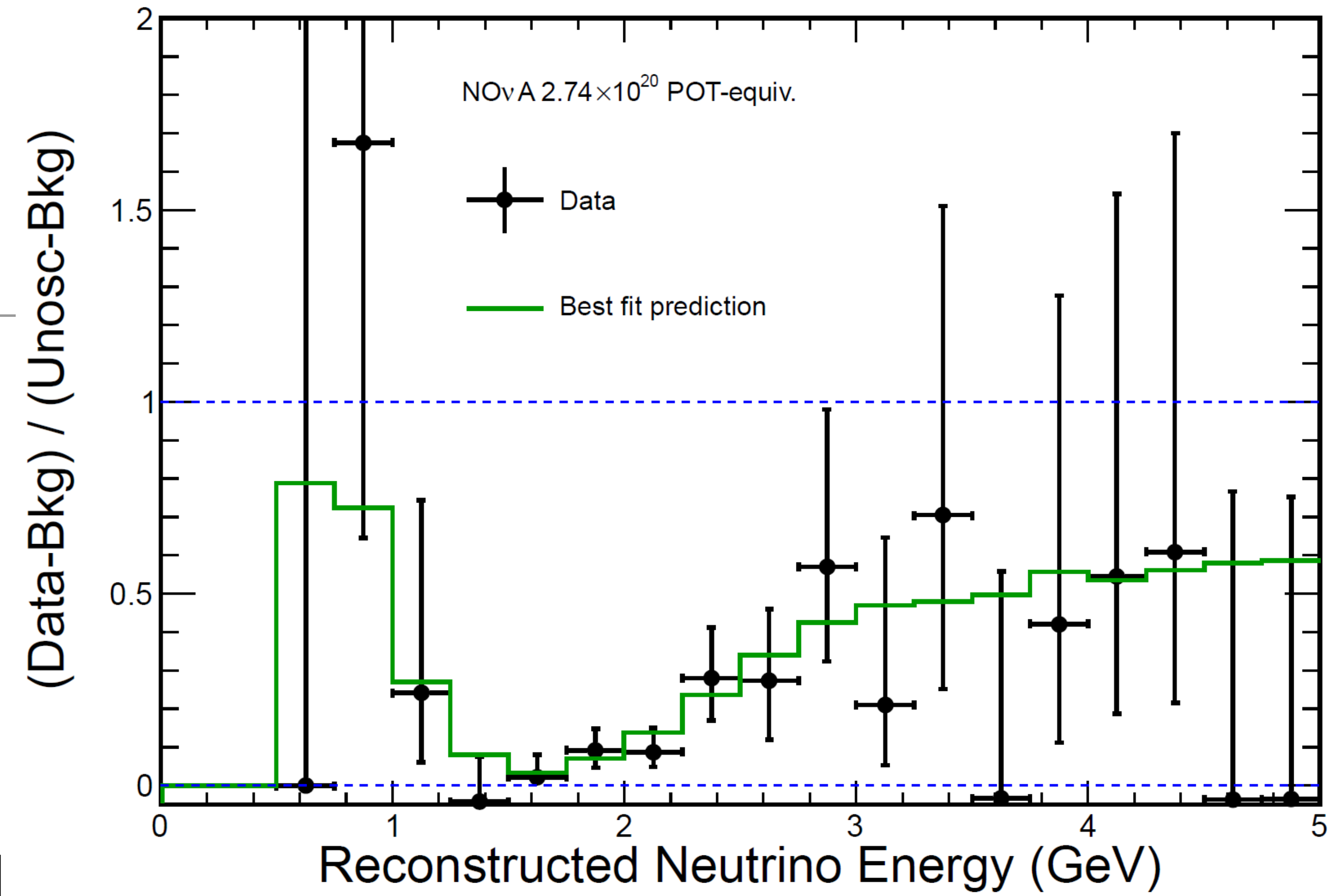
NOvA Far detector muon neutrino spectrum

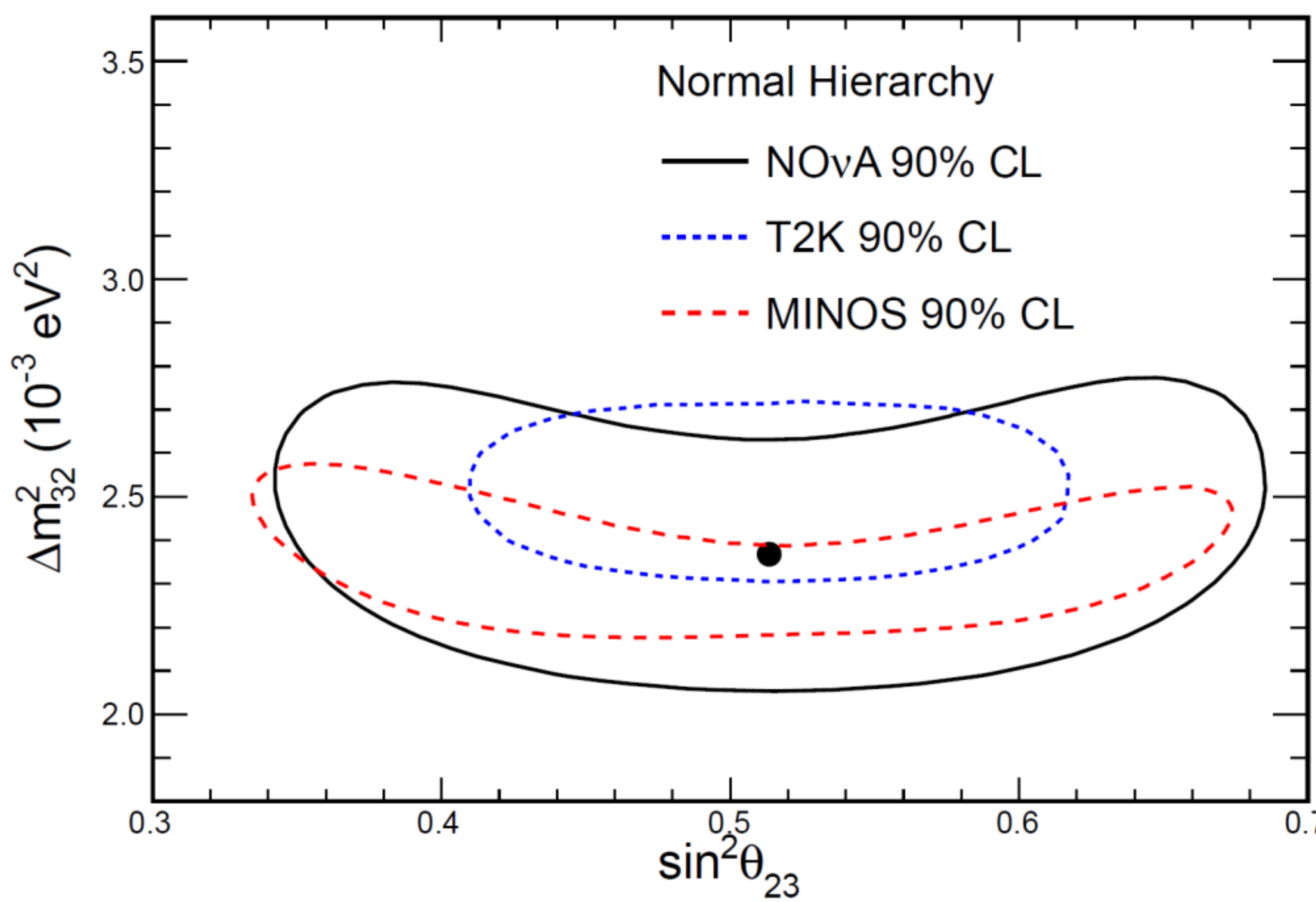
201 events expected before oscillations
33 events observed

NOvA
ν_μ Disappearance

$$\Delta m^2_{32} = +2.37^{+0.16}_{-0.15}\ \text{[normal ordering]}$$
$$\Delta m^2_{32} = -2.40^{+0.14}_{-0.17}\ \text{[inverted ordering]}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

NOvA Preliminary

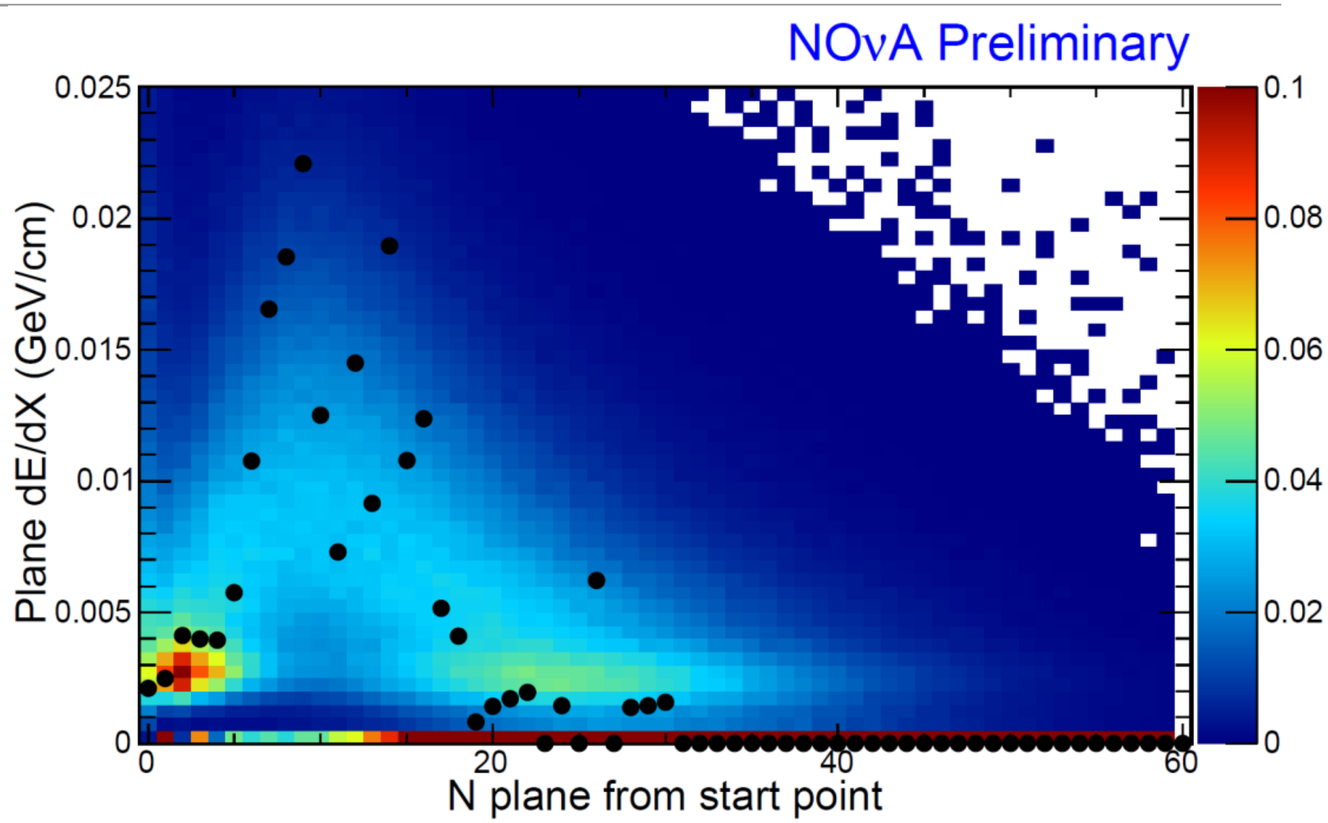




ν_e Identification in NOvA

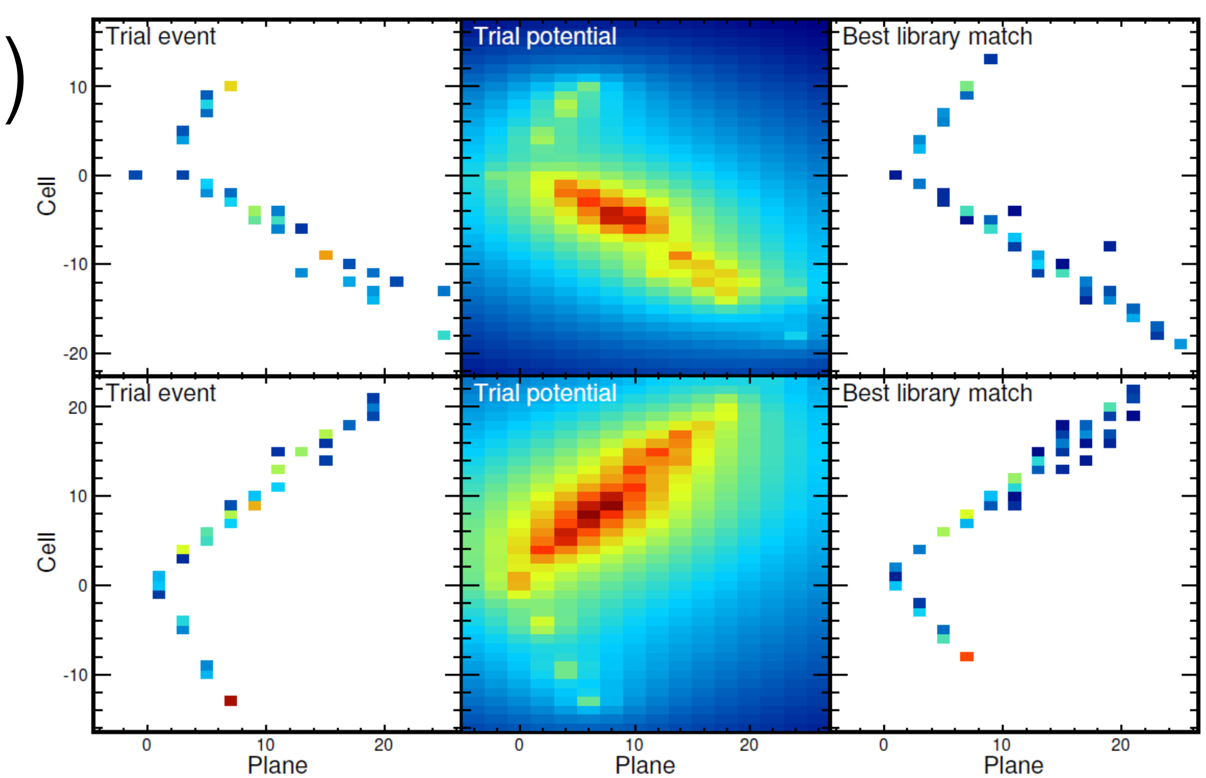
Likelihood Identifier ("LID")

Tests event longitudinal and transverse shower dE/dx profiles against probability density functions for e/μ/π/p hypotheses



Library Event Matching ("LEM")

Tests entire event topology against a large library of simulated neutrino signal and background events. Assigns event characteristics according to top matches.



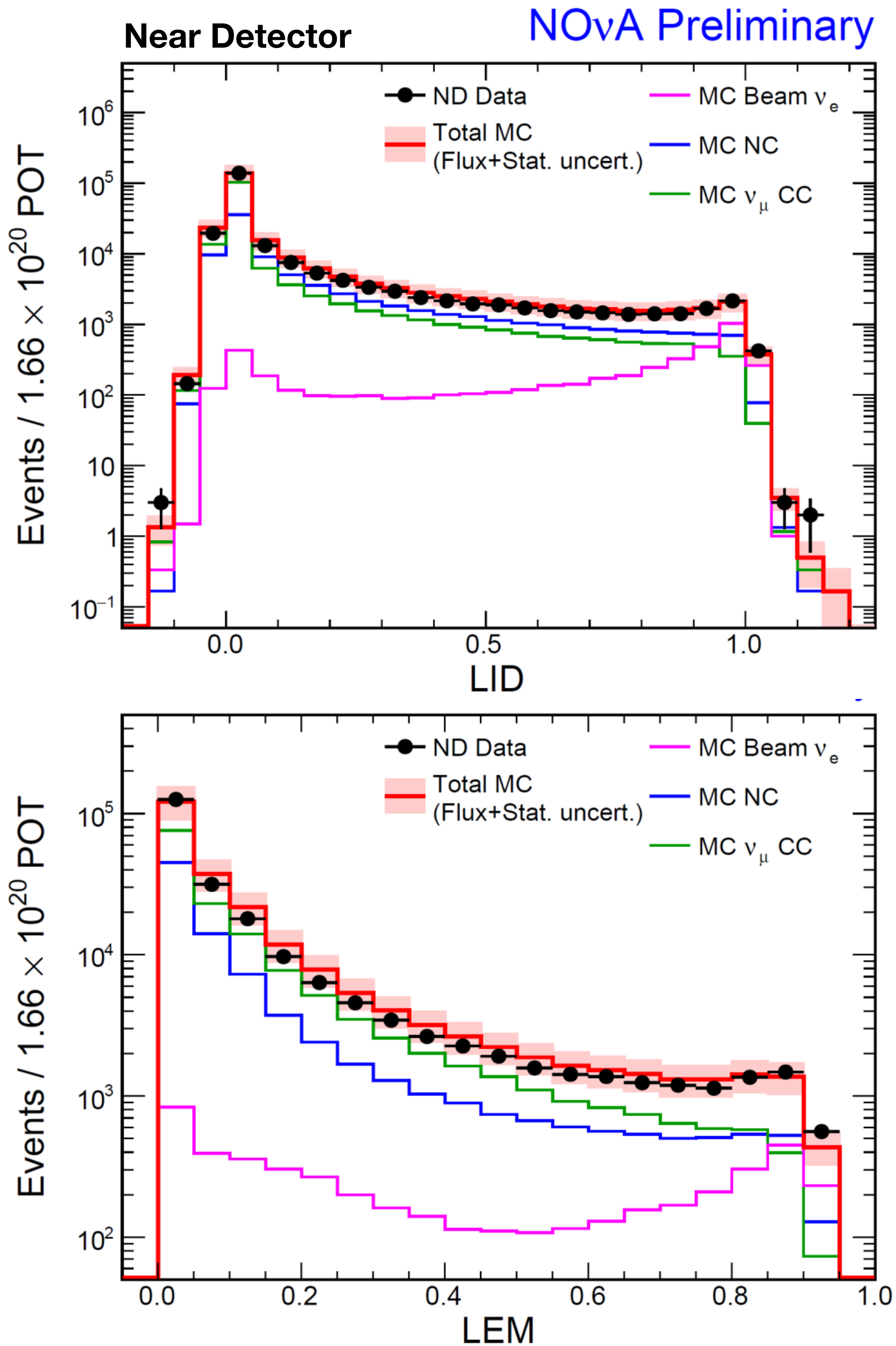
NOvA ν_e Selection

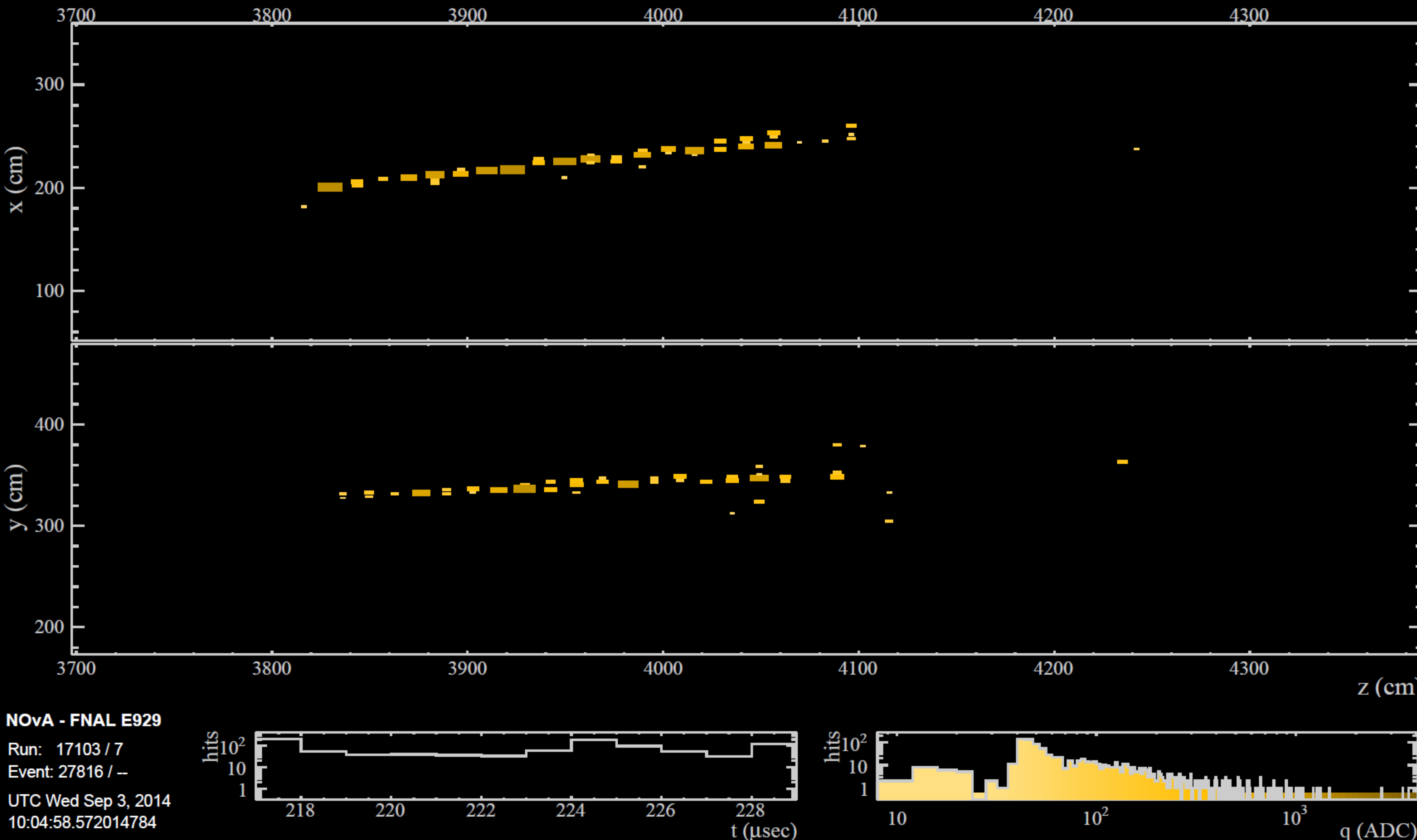
Based on near detector measurements predict:

1 ± 0.1 background events

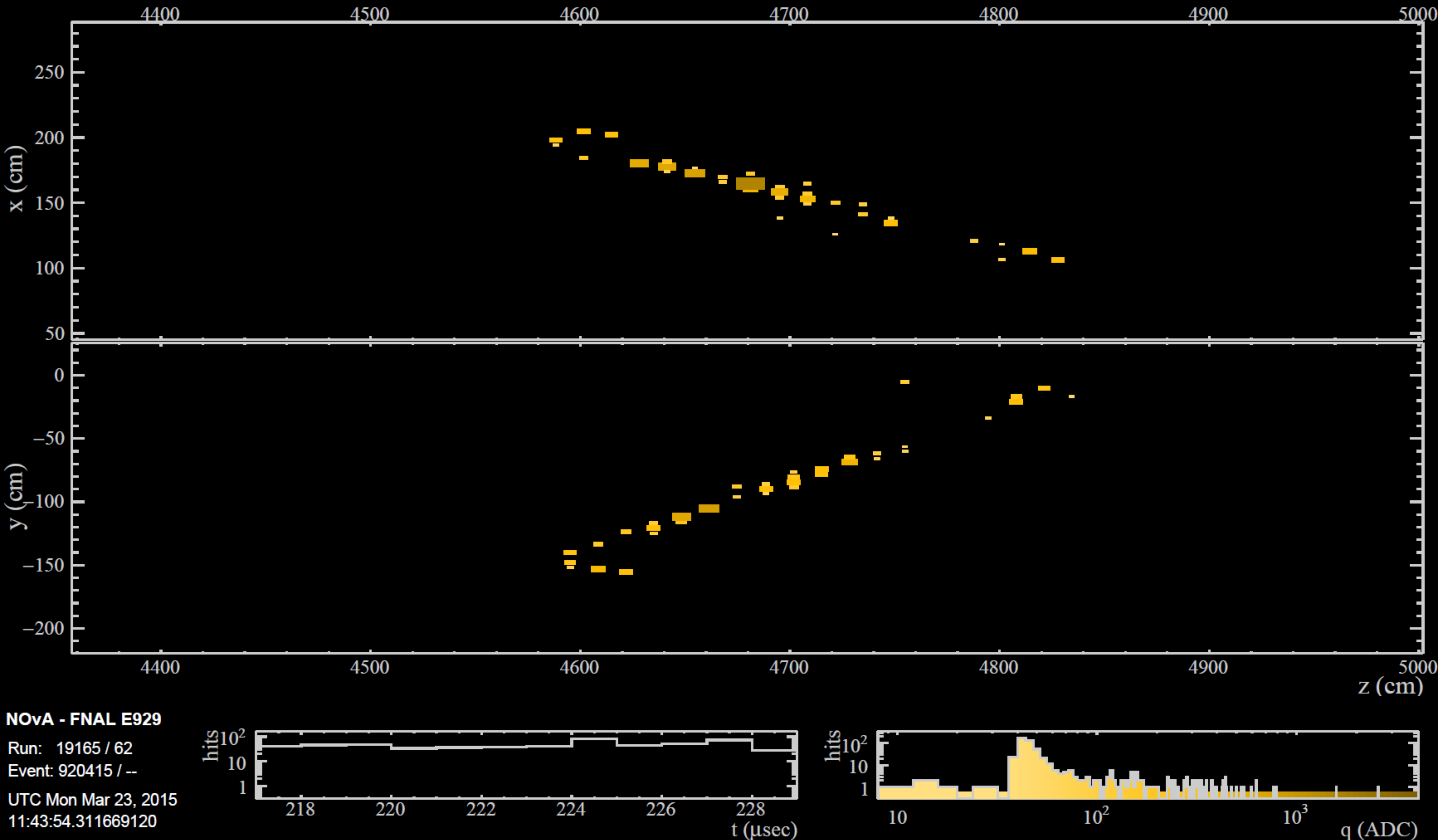
2 ± 0.3 signal [IO $\delta_{CP}=\pi/2$]
6 ± 0.7 signal [NO $\delta_{CP}=3\pi/2$]

at far detector for $\sin^2\theta_{23}=0.5$





NOvA ν_e Candidate



NOvA ν_e Candidate

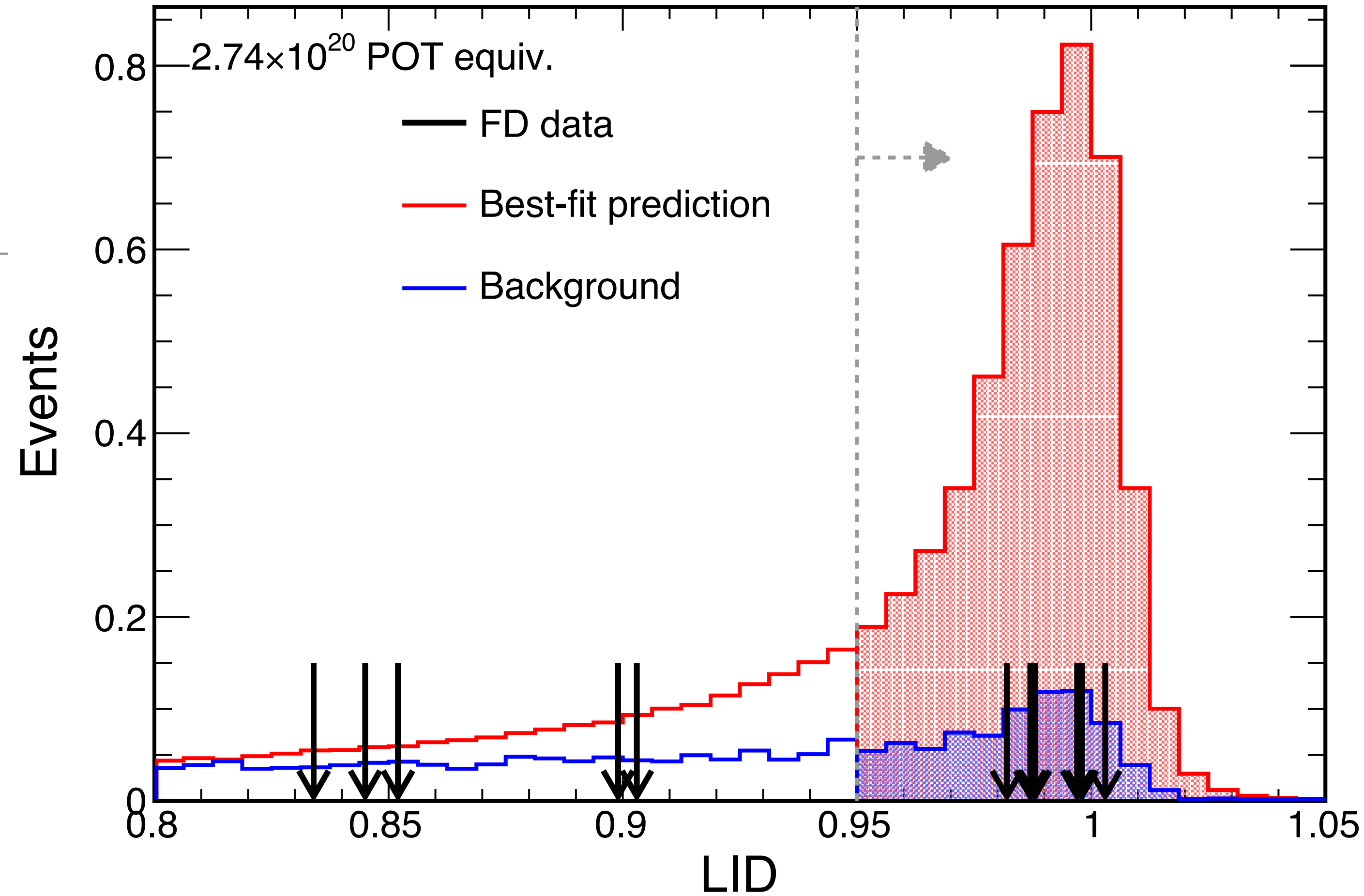
NOvA Electron Neutrino Appearance

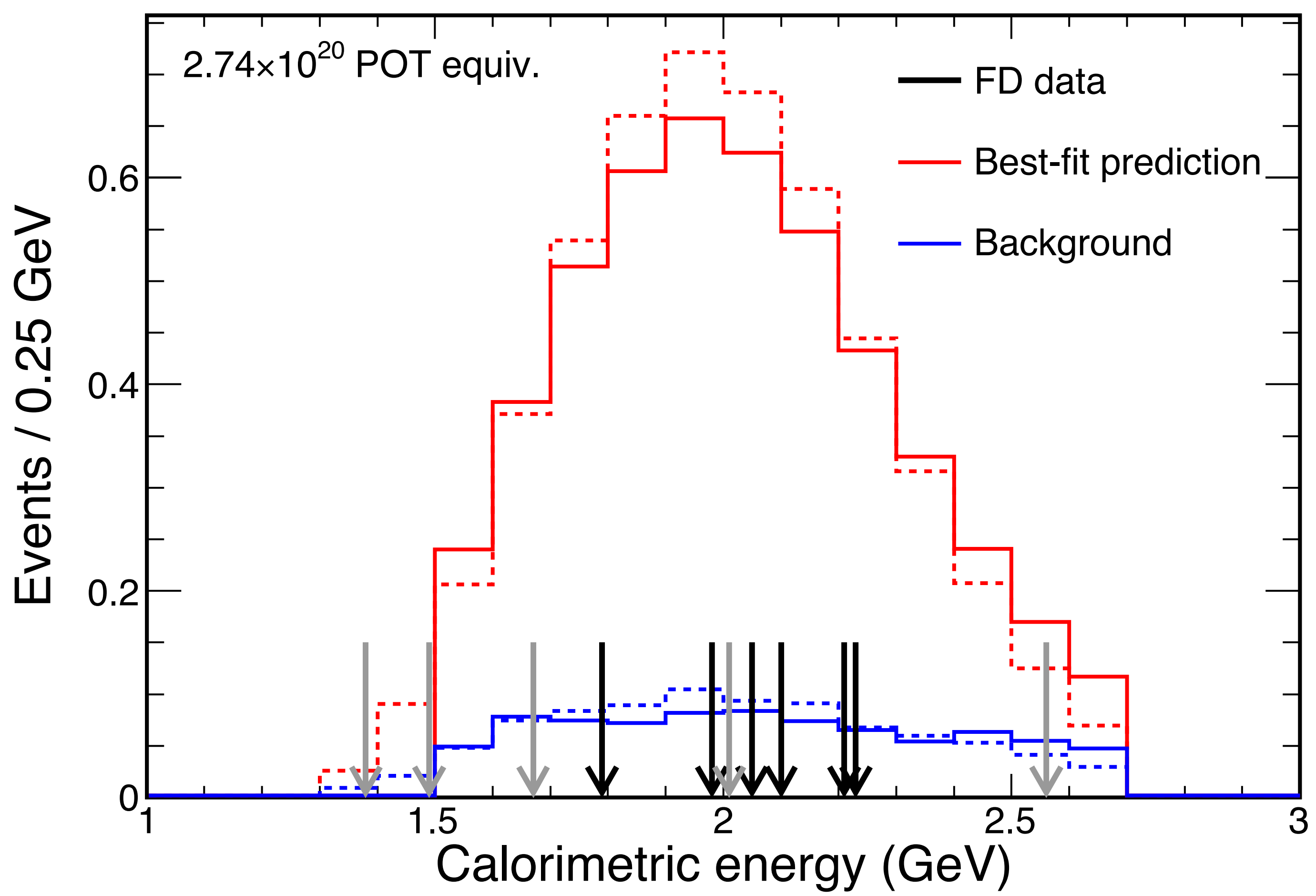
- These select **6 (LID)** and **11 (LEM)** events. All 6 of the LID events are selected by LEM. Expected **background is 1 event** for each. These are **3.3σ** and **5.5σ** significant excesses over background.

- LID and LEM have 60% overlap, determined from simulation and checked in NOvA near detector. The P-value for selecting the combination (11:6/5/0) is 11%.

- Top plot shows the LID particle IDs for the 11 selected events. The LID&LEM events are to the right of the dashed line. The 5 LEM-only events are shown to the left. Bottom plot shows the energy spectrum of the 11 events. LID are in black, LEM in gray.

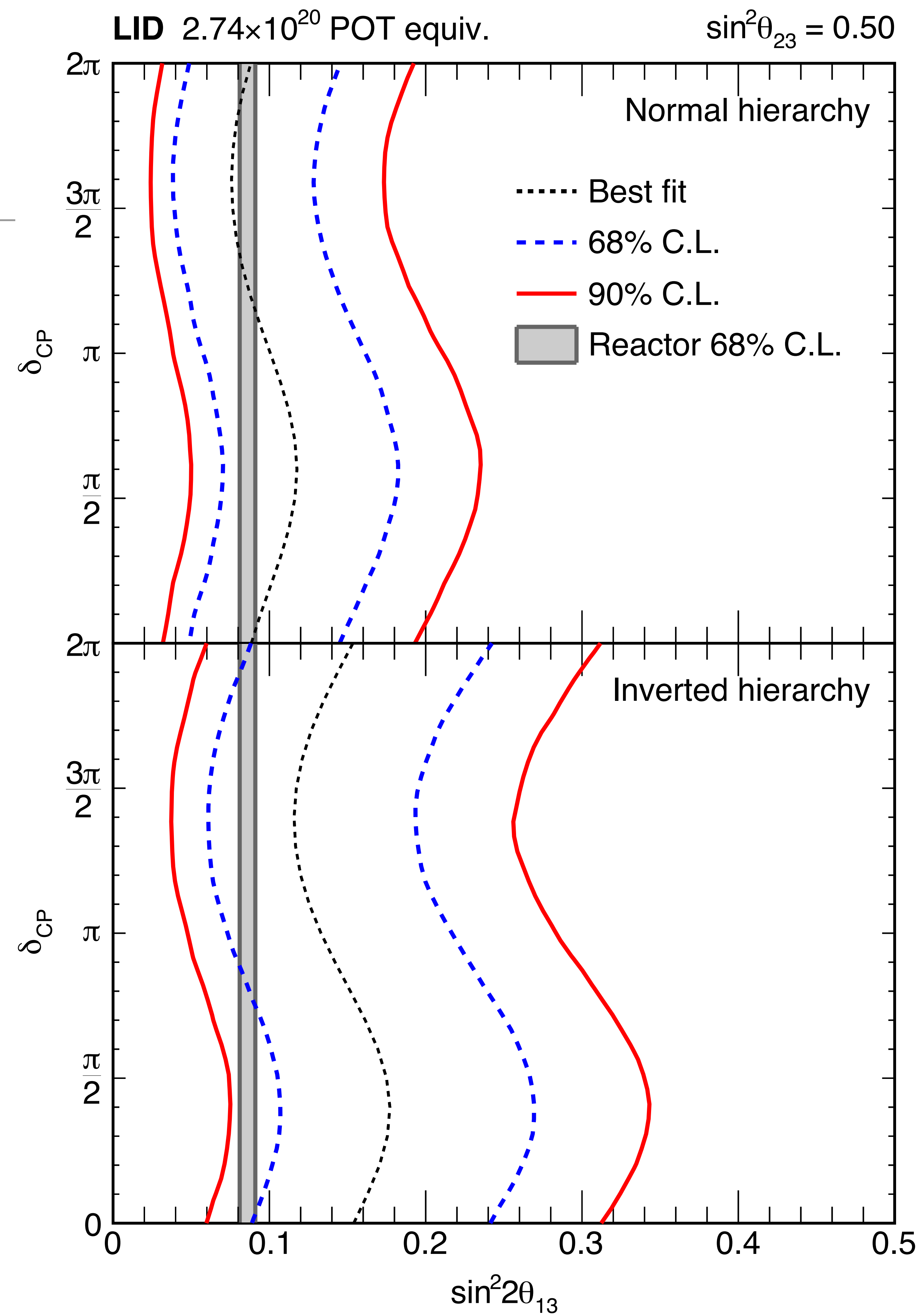
NOvA Preliminary





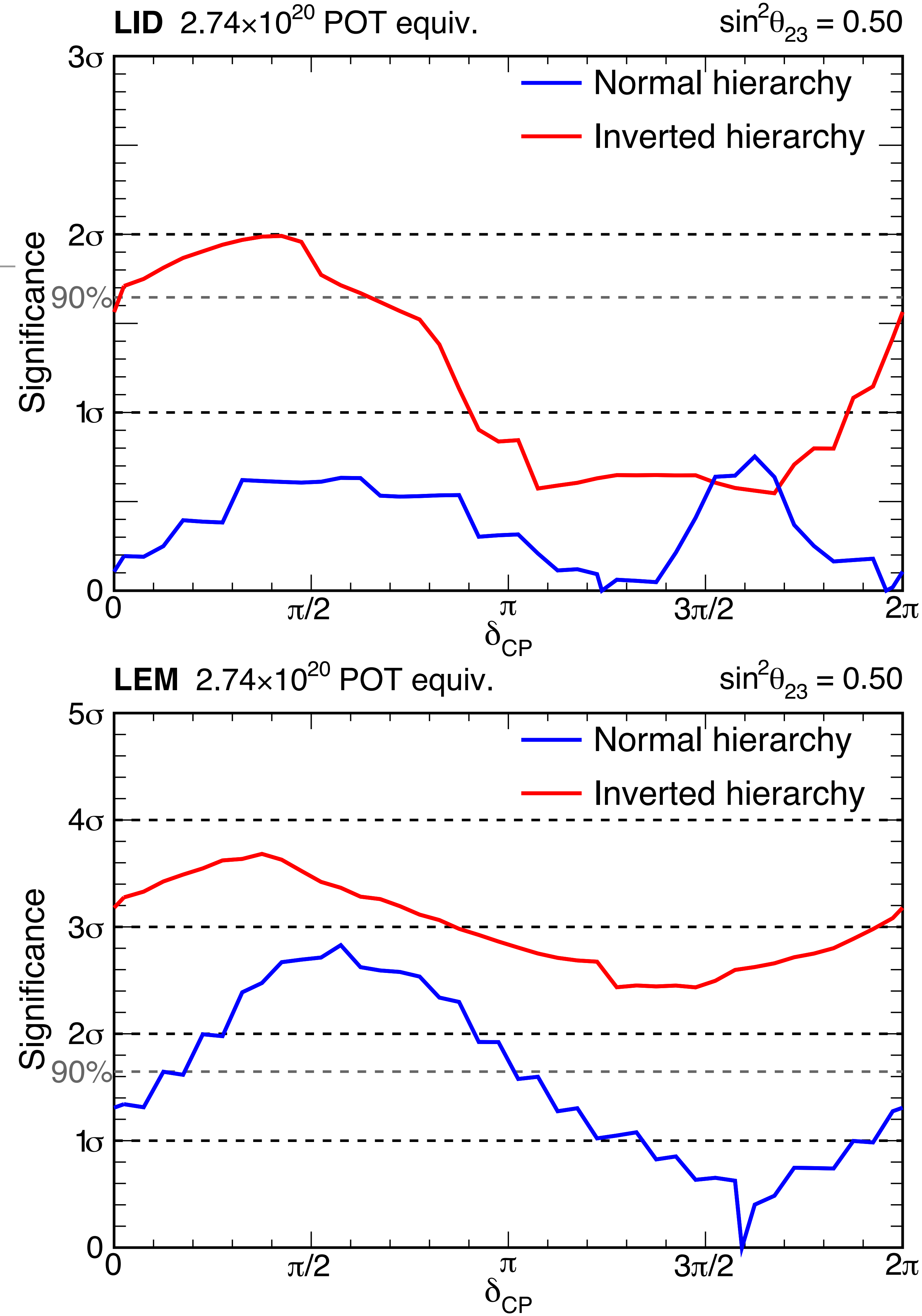
NOvA Electron Neutrino Appearance

- Results show good consistency between NOvA (s-cuves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering
- This plot is for LID selector (n=6). For LEM (n=11) the s-curves shift ~x2 to the right increasing tension for the inverted mass ordering. See next page.



NOvA Electron Neutrino Appearance

- If we take the reactor measurement of θ_{13} as an input we can ask how well the NOvA event counts fit to particular choices of the mass ordering and δ_{CP}
- Both LID and LEM prefer normal mass ordering with δ_{CP} between π and 2π
- For LID (n=6, top plot) there is some tension with the inverted hierarchy especially for δ_{CP} near $\pi/2$
- For LEM (n=11, bottom plot) the inverted hierarchy is everywhere disfavored at 2σ
- ***Beware of trials factor of choosing to only look at LEM results*** - true answer is most likely somewhere in between top and bottom results. We will have roughly x2 more data to report at Neutrino in July, 2016
- A further note: The jagged contours are a result of small-number statistics



Summary

Measurements using atmospheric neutrinos, reactor neutrinos and long-baseline neutrinos form a consistent picture

- Large θ_{23} ($0.4 < \sin^2\theta_{23} < 0.6$)
- Precisely known $\theta_{13} = 8.4^{o}$
- Consistent hints favoring
    - $\pi<\delta_{CP}<2\pi$
    - normal mass ordering
- First data from NOvA strengthens this picture with more data to come